INDUSTRIAL PLANTS RELIABILITY EVALUATION

BY

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عمادة الدراسات العليا
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Dedicated to

My Father, Mother

and

My two sons Meshari and Waleed

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All praise be to Allah the Lord of the worlds, for having guided me at every stage of my life. I seek His mercy, favor and forgiveness. I feel privileged to glorify His name in the sincerest way through this small accomplishment.

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Contents

Acknowledgements i

List of Tables vi

List of Figures ix

Nomenclature x

Abstract (Arabic) xi

Abstract (English) xii

1. Introduction. 1

1.1 Introduction 1
1.2 Distribution System Reliability. 2
1.2.1 System Reliability Indices. 3
1.2.2 Customer Reliability Indices. 5
1.2.3 Average Service Availability Index. 6
1.3 Thesis Motivations. 7
1.4 Thesis Objective 9
1.5 Thesis Scope 9

2. Literature Survey **11**

3 Proposed Industrial Plants Reliability Indices **22**

3.1 Introduction 22
3.2 Plant Equipment Average Interruption Frequency Index . 23
3.3 Plant Individual Equipment Average Interruption Frequency Index 25
3.4 Plant Average Interruption Frequency Index 26
3.5 Plant Average Interruption Duration Index 27

3.6 Plant Average availability Index 29
3.7 Plant Shut down cost Index 30
3.8 Plant annual Cost Saving Index 32

4. Comparison Between the Existing and the Proposed Indices 34

4.1 Introduction 34
4.2 Non Critical Loads 35
4.3 Loads with different KVA ratings. 42
4.4 Plant Re-Startup Time. 53

5. Evaluation of the Proposed Reliability Indices through case studies. 58

5.1 Introduction. 58
5.2 Proposed Industrial Plant Reliability Indices before arranging the loads 59
5.3 Proposed Industrial Plant Reliability Indices after arranging the loads. 76
5.4 The effect of re-arranging the loads on the industrial Plants Reliability indices. 88

6. Proposed Industrial Plants Reliability Upgrading Evaluation through case 89

6.1 Introduction. 89
6.2 Upgrading Assumptions 90
6.3 Case Studies 92
6.3.1 Existing Substation reliability indices calculation before Upgrade. 95
6.3.2 Case A: Upgrading the SE bus bar BB01 to DENO bus bar. 108
6.3.3 Case B: Upgrading the SE bus bar BB01 to DENC bus bar. 115
6.3.4 Case C: Upgrading the DENO bus bar BB02 to DENC Bus bar. 122
6.3.5 Case D: Upgrading the SE bus bar BB01 to DENO Bus bar and DENO bus bar BB02 to DENC bus bar. 129
6.3.6 Case E: Upgrading the SE bus bar BB01 to DENC Bus bar and DENO bus bar BB02 to DENC bus bar. 133

6.4 Upgrading Decisions.. 137

7. Conclusions **140**

7.1 Conclusions. 140
7.2 Recommendation for future work 141

APPENDICES

A. Industrial Plant Soft Ware User Guide **142**

B. Industrial Plants Reliability Indices Calculation Flowchart **156**

Bibliography **157**

Vita **159**

List of Tables

4.1: Existing indices Non Critical Load Equipment. 38

4.2: Existing Indices Non Critical Load Bus.bar Interruption 39

4.3: Non Critical Loads Bus.bar Existing Reliability Indices. 41

4.4: Existing Indices Loads with different KVA Equipment 44

4.5: Existing Indices Before Changing the Load KVA rating Bus bar Interruption 46

4.6: Before Changing the Load KVA rating Bus bar Existing Reliability Indices 48

4.7: Existing Indices After Changing the Load KVA rating Bus.bar Interruption 50

4.8: Before Changing the Load KVA rating Bus.bar Existing Reliability Indices 52

4.9: Proposed Reliability Indices Bus.bar 54

4.10: Proposed Industrial Plant Reliability Indices With 0 hours Restart up time. 56

4.11: Proposed Industrial Plant Reliability Indices With 15 hours Restart up time. 56

5.1: Interruption Data for Plant A. 65

5.2: BBO1 Interruption before arranging the loads 67

5.3: BBO2 Interruption before arranging the loads 69

5.4: BBO3 Interruption before arranging the loads 71

5.5: Plant Interruption before arranging the loads 73

5.6: Reliability summary data before arranging the loads 75

5.7: Industrial Plant Reliability indices before arranging the loads . 75

5.8: BBO2 Interruption after arranging the loads 82

5.9: BBO3 Interruption after arranging the loads 83

5.10: Plant Interruption after arranging the loads. 85

5.11: Reliability summary data after arranging the loads 87

5.12: Industrial Plant Reliability indices after arranging the loads . . 87

6.1: Interruption Data for Plant A. 94

6.2: BBO1 Interruption before upgradation 101

6.3: BBO2 Interruption before upgradation 102

6.4: BBO2 Interruption before upgradation 104

6.5: Plant Interruption before upgradation. 105

6.6: Plant summary data before upgradation. 107

6.7: Industrial Plant Reliability Indices before Upgradation. 107

6.8: Case A: BBO1 Interruption. 111

6.9: Case A: Plant Interruption. 112

6.10: Case A: Plant summary data 114

6.11: Case A: Industrial Plant Reliability Indices 114

6.12: Case B: BBO1 Interruption 118

6.13: Case B: Plant Interruption 119

6.14: Case B: Plant summary data 121

6.15: Case B: Industrial Plant Reliability Indices 121

6.16: Case C: BBO2 Interruption 125

6.17: Case C: Plant Interruption 126

6.18: Case C: Plant summary data 128

6.19: Case C: Industrial Plant Reliability Indices 128

6.20: Case D: Plant Interruption. 130

6.21: Case D: Plant summary data.. 132

6.22: Case D: Industrial Plant Reliability Indices 132

6.23: Case E Plant Interruption Table 134

6.24: Case E: Plant summary data 136

6.25: Case E: Industrial Plant Reliability Indices 136

6.26: Plant Upgrading Evaluation Summary 139

List of Figures

4.1: Single Line Diagram BB01. 36

4 .2: Single Line Diagram BB02 43

5.1: Single Line Diagram BB01 Before arranging the load 61

5.2: Single Line Diagram BB02 before aranging the loads. 62

5.3: Single Line Diagram BB03 before arranging the load 63

5.4: Single Line Diagram BB01 after arranging the load 78

5.5: Single Line Diagram BB02 after arranging the loads 79

5.6: Single Line Diagram BB03 after arranging the load 80

6.1: Single Line Diagram BB01 before upgrading the bus-bar 97

6.2: Single Line Diagram BB02 before upgrading the bus-bar. . . . 98

6.3: Single Line Diagram BB03 before upgrading the bus-bar 99

6.4: Single Line Diagram BB01 after upgrading the SE to DENO . . 109

6.5: Single Line Diagram BB01 after upgrading the SE to DENC . . 116

6.6: Single Line Diagram BB02 after upgrading the DENO
to DENC 123

Nomenclature

CEI	Critical equipment interrupted
CEC	Critical equipment connected
ICEI	Individual Critical equipment interrupted.
PI	Plant Interruption
CEID	Critical Equipment Interruption Duration
PSD	Plant Startup Duration
PPC	Plant Production Cost
PSCBM	Plant Shutdown Cost before modification
PSCAM	Plant Shutdown Cost After modification
PMCBM	Plant Maintenance Cost before modification
PMCAM	Plant Maintenance Cost After modification
AIOEY	Annual Investment of Equipment Yearly

THESIS ABSTRACT

Name	: Meshal Abdullah AL-Anazi
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The existing reliability indices are not appropriate to asses the reliability of the industrial plant. In this thesis, seven reliability indices are proposed. The new industrial plant reliability indices were compared with IEEE-Std1366 taking into consideration: the non-critical loads, the effect of changing the kVA rating, and the plant re-startup time. Adapting the proposed reliability indices, the industrial plants with different substation configurations can be evaluated. These indices, based on different studies supported by cost analysis, should provide a guide to the plant management to asses and decide whether the plant requires a modification or not. The effect of re-arranging the plant loads and the impact on the reliability indices is also studied.

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خلاصة الرسالة

الاســــــم : مشعل عبد الله العتري

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من خلال المسح للأبحاث المنشورة في المجلات العلمية وجد أن مؤشرات الموثوقية الحالية غير مناسبة لتقييم المنشآت الصناعية . لهذا فقد أقترح في هذه الرسالة سبعة مؤشرات موثوقية جديدة . ولقد تم مقارنة هذه المؤشرات بمواصفات معهد مهندسي الكهرباء والإلكترونيات - ١٣٦٦ (IEEE-std 1366) أخذا" في الاعتبار : الأحمال الغير فعالة (non-critical loads) ، تأثير تغير الكيلوفولت أمبير والوقت المتطلب لتشغيل المنشأه الصناعية . باستخدام مؤشرات الموثوقية الجديدة يمكن أيضا"تقييم المنشأه الصناعية ذات المحطات الفرعية المختلفة .

يمكن استخدام هذه المؤشرات الجديدة من خلال دراسات عديدة للمنشأه أخذا" في الاعتبار معامل التكلفة مما يساعد إدارة المنشأه لتقيم وتقرر الحاجة إلى التطوير في المنشأه . في هذه الرسالة تم أيضا" دراسة إعادة هيكلة الأحمال وتأثيرها على موثوقية المنشأه الصناعية .

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران ـ المملكة العربية السعودية

يونيو ٢٠٠٢م

Chapter 1

INTRODUCTION

1.1 Introduction

Reliability, in general, is one of the main evaluation factors in different fields. An example is evaluating the reliability of a plant or car life, building power supply, airplane and etc. The methods of evaluating reliability would differ depending on the area that needs to be evaluated. Evaluating a building structure is different from evaluating a car life. The acceptable level of reliability is based on the customer judgment and level of acceptance. The cost of accepting reliability is very important in deciding whether to fix, replace or expand the component.

One of the major fields that have to be reliable is power system. Power system is divided into three areas: generation, transmission and distribution. Generation and transmission have been researched thoroughly with many reliability evaluations studies. However, there was a less attention to the distribution system in the last two decades.

1.2 Distribution System Reliability

Electrical distribution system is classified according to the load type: industrial, commercial, residential, etc. The total cost due to the power failure in an industrial plant is much higher than that of in commercial or residential loads.

IEEE standard 1366 "IEEE Trial – Use Guide for Electric Power Distribution Reliability" was drafted to evaluate the distribution system reliability. The existing distribution system reliability indices can be characterized into system reliability indices and customer reliability indices. The system reliability indices evaluate the power system using either load or customer based indices. The customer reliability indices evaluate the power system based on customer as given below [1]:

1.2.1 System Reliability Indices

1.2.1.1 Customer based indices

1.2.1.1.1 System Average Interruption Frequency Index; (SAIFI)

This index is designed to give information about the average frequency interruption per customer, which means in average how many interruptions is one customer having.

$$SAIFI = \frac{Total\ Number\ of\ Customer\ Interruptions}{Total\ Number\ of\ Customers\ Served} \tag{1.1}$$

The lower limit for this index is zero when there is no interruption, while there is no higher limit for this index.

1.2.1.1.2 System Average Interruption Duration Index; (SAIDI)

This index is designed to give information about the average duration of interruption per customer in minutes that means how many minutes of average interruptions each customer is having.

$$SAIDI = \frac{\sum Customer\ Interruption\ durations}{Total\ Number\ of\ Customers\ Served} \tag{1.2}$$

The lower limit for this index is zero when there is no interruption while there is no higher limit for this index.

1.2.1.2 Load based indices

1.2.1.2.1 Average System Interruption Frequency Index; (ASIFI)

This index is designed to give information about the system average frequency of interruption.

$$ASIFI = \frac{Connected\,KVA\,Interrupted}{Total\,Connected\,KVA\,served} \tag{1.3}$$

The lower limit for this index is zero when there is no interruptions while there is no higher limit for this index. This index is normally used for industrial plants.

1.2.1.2.2 Average System Interruption Duration Index; (ASIDI)

This index is designed to give information about the system average Duration of interruption.

$$ASIDI = \frac{Connected\,KVA\,Duration\,Interrupted}{Total\,Connected\,KVA\,served} \tag{1.4}$$

The lower limit for this index is zero when there is no interruption, while there is no higher limit for this index. This index is used for industrial plants.

1.2.2 Customer Reliability Indices

1.2.2.1 Customer Average Interruption Duration Index; (CAIDI)

This index is designed to give information about the average time required to restore service to the average customer per interruption.

$$CAIDI = \frac{\sum Customer\ Interruption\ Duration}{Total\ Number\ of\ Customer\ Interruptions} \qquad (1.5)$$

The lower limit for this index is zero when there is no interruption, while there is no higher limit for this index.

1.2.2.2 Customer Total Average Interruption Duration index; (CTAIDI)

This index is designed to give information about the customer average duration of interruption for those customers experiencing interruptions only.

$$CTAIDI = \frac{\sum\ Customer\ Interruption\ Duration}{Total\ Number\ of\ Customers\ Interrupted} \qquad (1.6)$$

The lower limit for this index is zero when there is no interruption while there is no higher limit for this index.

1.2.2.3 Customer average interruption frequency index; (CAIFI)

This index is designed to give information about the customer average frequency of interruption for those customers experiencing interruptions only.

$$CAIFI = \frac{\text{Total Number of Customer Interruptions}}{\text{Total Number of Customers Interrupted}} \tag{1.7}$$

The lower limit for this index is zero when there is no interruption, while there is no higher limit for this index.

1.2.3 Average Service Availability Index; (ASAI)

This index is designed to give information about the percentage that a customer has been provided with power during one year or reporting period.

$$ASAI = \frac{\text{Customers Hours Service Availability}}{\text{Customers Hours Service Demand}} \tag{1.8}$$

The minimum for this index is zero, while the maximum for this index is 1.

1.3 Thesis Motivation

Although the existing SAIDI, SAIFI, CAIDI, CAIFI and ASAI indices are used for industrial plants but they are not applicable for this purpose due to two main reasons. For industrial plants, there are no customers, so none of the customer indices can be applied. Other indices, that consider the kVA load such as ASIDI, ASIFI, will not work for industrial plant reliability, since there are non-critical loads that would not affect the plant reliability if lost; i.e. lighting, A/C, etc.. The indices are also controlled by the KVA rating of the tripped equipment, which would vary for one plant with fixed shutdown duration by changing the KVA load rating.

There are many industrial plants in Saudi Arabia and all over the world using the old IEEE-Std1366 reliability indices in evaluating the plants reliability. The IEEE-Std1366 indices are applicable for commercial and residential but not for industrial plants. So the industrial plants need reliability indices that match their needs and criteria to evaluate real plant reliability.

Measuring the plant shutdown cost index and plant modification cost index will help industries to study different options for plant substations modification. All the cost indices are based on the KVA rating which might work for generation company but not for industrial plants. The industrial plants production shutdown cost is much higher than the equipment KVA rating cost, which is not considered in the existing indices.

The industrial plants reliability indices assist in determining the acceptable level of service reliability to industrial plants. The comparison of the performance of alternative system configurations in the planning process helps to determine the most suitable configuration for a plant.

There is a need to evaluate the industrial plant reliability in a logical way that calculates the real plant reliability indices. Most of the industrial plant equipment are mechanical, such as pumps, compressors, fans those are normally operated electrically. To evaluate the industrial plant reliability the process equipment reliability need to be evaluated. If the process equipment fails, the plant product would be lost. This figure would vary, depending on whether a back up equipment is installed for the process equipment or not.

1.4 Thesis Objective

Guided by the above motivation, the present work proposes to do the following:

- Propose seven industrial plants reliability indices.
- Compare the existing indices with the proposed industrial plants reliability indices.
- Apply the proposed industrial plant reliability indices to different substation configurations.
- Study the effect of re-arranging the loads in the industrial plants reliability indices.

1.5 Thesis scope

Chapter two of the thesis presents a literature survey on reliability indices. New reliability indices taking the process equipment into consideration are proposed in chapter three to calculate the industrial plants reliability.

The proposed industrial plants reliability indices compared with the existing reliability indices as shown in chapter four. The effect of rearranging the plant loads on the reliability indices studied in Chapter five. The cost saving index based on different upgrading options studied in chapter six. A conclusion and recommendations for future work is given in chapter seven.

Chapter 2

LITERATURE SURVEY

Several indices for distribution system, which includes industrial plant reliability have been developed and calculated in IEEE Std 1366. The indices based on either number of customers or the connected kVA loads. Some of the well-known reliability indices are system average interruption frequency index (SAIFI) and system average interruption duration index (SAIDI). SAIFI is designed to give information about average frequency of sustained interruptions per customer over pre-defined area. SAIDI referred to customer minutes of interruption[1].

Other known indices are customer average interruption index (CAIDI), Customer total average interruption duration index (CTAIDI) and customer average interruption frequency index (CAIFI). CAIDI represents the average time required to restore service to the average customer per sustained interruptions. CTAID give the average duration of sustained interruption for those customers experiencing sustained interruptions. CAIFI gives the average frequency of sustained interruption for those customers experiencing sustained interruptions[1].

Other known indices are Average service availability index (ASAI), Average system interruption frequency index (ASIFI) and Average system interruption duration index (ASIDI). ASAI give the percentage that a customer has power provided during one year or the defined reporting period. ASIFI gives information on the system average frequency of interruption based on load rather than number of customer. ASIDI gives information on the system average duration of interruption based on load [1].

A survey was carried on 100 utilities in 1990 and on 205 utilities in 1995 for the purpose of gathering information on reliability and incorporating it into the IEEE-Std1366 Trial use guideline for distribution reliability indices draft guideline [2]. The survey result shows that most commonly used indices in the utilities were the SAIFI, SAIDI, CAIDI, and ASAI. The two basic categories of reliability indices are customer-based indices and load-based indices. The customer based indices records the frequency and the duration of outages for individual customers and mostly informative in mainly residential areas. Load based indices were helpful in monitoring the frequency and duration of interruption of load and are relevant for circuits that are mostly industrial/commercial feeders [2].

If a feeder serves one plant, then the customer-based indices may be misleading. When companies use load based indices, the average peak load or transformer connected capacity is used to calculate the values. Often these indices are used solely due to a lack of customer information. In 1995, only 5-8% of responding utilities reported using load based indices. This is likely to change in the future [2]. Although the survey done in large number of utilities, it shows that there is a lack of evaluating industrial plants reliability. Most of the plants depend on conventional methods using the mentioned reliability indices in IEEE-Std1366. This support a need for new reliability indices that evaluate the industrial plant reliability based on process equipment interruption.

Distribution system and industrial systems reliability evaluation program (DISREL) for power distribution system reliability assessment and value based distribution system resource analysis were used to study the distribution system reliability [3]. DISEREL uses the mentioned reliability indices in IEEE-Std 1366 and relate them to total cost index based on KWHr. The outage and system costs were proposed where the total cost is the summation of the outage and the system costs [3].

Adding more components, both customer and system reliability improved significantly, proving increased system cost and reduced outage cost will achieve the optimum Total cost. Two case studies with different configurations were evaluated using the cost formula trying to reach the optimum total cost and to select it as the best option in modifying the substation [3].

Two examples applied to continuous process plants were described [4]. The first example shows how the power system upgrades have been justified bases on reducing the risk of plant power system failure. The cost to re-start the process can be as high as $100 million[4].

The four most popular reliability indices used in reliability analysis are SAIFI, CAIFI, which measure the frequency and SAIDI, CAIDI that measures the duration [5]. There are some industries where a five minute outage is nearly as damaging to productivity as a one-hour outage - for computer and robotic equipment requires hours to re-set and restart or they have such a long production process so sensitive to power fluctuations that they have to start over from the beginning if there is even a slight interruption. So for these customers five-five minute outages are far more damaging than a single, five-hour outage [5].

Reliability evaluation deals with how adequately the distribution transformers, secondary circuits and customer service connections perform their intended function [6]. The basic indices normally used to predict reliability of a distribution system are; the load point failure (λ), average outage duration and annual unavailability

(U) and the most common system indices SAIFI, SAIDI, CAIDI, ASAI, Average Service Unavailability Index (ASUI), Average Energy Not Supplied (AENS) [6]. The ability to evaluate the cost in addition to the traditionally reliable indices has several potential applications in distribution system planning [6]. The IEEE-Std 1366 reliability indices used with cost index based on KW to evaluate different circuit configurations [6].

Simplified procedure to determine the reliability indices of radial distribution system with branches used failure rate, average outage and network reduction technique to calculate the mentioned IEEE-Std 1366 reliability indices SAIFI, SAIDI, CAIDI, ASAI, and ASUI. A network reduction technique is illustrated to simplify the analytical process [7].

Considerable attention has been devoted in the last few years to the reliability evaluation of composite generation and transmission systems, with relatively little effort applied to the distribution domain, particularly low voltage distribution systems [7]. Data on utility failure statistics show that the distribution system failures are approximately 80% of the total customer interruption [7].

A new active failure simulation for electric power distribution systems reliability assessment was studied [8]. The main principle depends on the first and the second order groups established for the nodes existing in basic minimal cut sets. The proposed algorithm is applied to a sample distribution network and three basic reliability indices are calculated [8].

A power system is expected to supply the customers with electric energy as economically as possible and with acceptable degree of reliability. Continuously available, 100% reliable, electric power supply is not physically possible due to failures, which are generally outside the control of engineers. Availability of the supply, however, can be maximized by increased investment during either the planning phase, and/or operating phase [8].

A method to adjust recalculated data to the historical data by using a parameter of multipliers after comparing the calculated data to the adjusted data were studied [9]. The method to calculate the optimal values of reliability indices for electric distribution systems were used [9]. Once the optimai reliability indices SAIFI and SAIDI are determined, the modification of existing systems or establishment of future systems can be done following these determined indices.

To many customers with sensitive electrical loads, reliability as well as the cost of energy may drive decisions such as where a new plant is to be located, whether an existing plant will be re-located, or whether a switch to a new energy provider will be pursued [9].

Distribution transformers reliability based on unscheduled outage per year and average unscheduled outage duration is given [10]. The multi-level hierarchical optimization method was used [10]. It starts by dividing the system into several sub-systems, and finds the optimal reliability indices for subsystems. Finally, the failure rate and the duration for all the substation components are optimized, so it will tell the plant owner not to exceed those values if he wants to keep the availability required [10].

Eighty percent of all the interruptions are due to failures in the distribution system [11]. The reliability assessment can be divided into two fundamental segments of measuring past performance and predicting future performance. Both applications involve in the collection of system outage data [11]. Evaluation of distribution system reliability based on failure rate and interruption duration using a multi-level hieratical procedure was studied [12].

The evaluation of reliability of worth index can be used to make decisions in distribution system planning and design [13]. The reliability worth index is termed the interrupted energy assessment rate (IEAR) and is obtained by relating the reliability indices to the customer cost of interruption data. The IEAR used both the unnerved energy and system cost formulas. Different examples were presented for different bus configurations in [13].

The basic function of an electric power system is to meet its energy and load demand at the lowest possible cost to its customers while maintaining acceptable levels of quality and continuity of supply [13]. What contributes an acceptable level can be examined in terms of costs and the worth to the customer providing an adequate supply [13].

Initial interruption cost, cost proportional to failure rate and cost of the modification have been evaluated using the kVA [14].

Reliability indices have begun to be standardized in the industry. However, the definition of means of establishing reliability indices is not universally accepted [15]. An individual utility may select indices that reflect its own operations in the most positive light. This may or may not take into account the best interest of the individual customer or reflect their requirements. Those needs may vary from one customer to another even though they are on the same feeder [15].

The cost per peak demand and the cost per annual energy demanded using the well-known reliability indices in meshed networks have been evaluated [16].

Although distribution systems have received less attention than generation systems, analysis of customer failure statistics shows that the distribution systems contribute as much as 90% towards the unavailability of supply to customers [16]. A sustained interruption can cost certain customers hundreds of thousands of dollars per hour. Even a momentary interruption can cause computer systems to crash and industrial plant processes to be ruined.

Chapter 3

Industrial Plants Reliability Indices

3.1 Introduction

In Chapter one the existing reliability indices and their respective equations were shownUsually in Industries, the kVA load indices such as ASIDI, ASIFI are used. These will not work for industrial plant reliability, since there are non-critical loads that would not affect the plant reliability if lost. Those indices are also controlled by the KVA rating which would vary with fixed shutdown duration. This might lead to unnecessary plant upgrade due to inaccurate figures of the plant reliability indices.

The proposed industrial plant reliability indices consist of seven new indices based on the critical equipment. The critical equipment can be defined as the equipment that would shutdown the plant if tripped. Based on these indices, the industrial plants with different substation configurations can be evaluated. These indices will help the plant management to asses and decide whether the plant requires a modification or not, based on different studies supported by cost analysis. Moreover, the plant engineers can use these indices to evaluate the plants and propose required modifications.

3.2 Plant Equipment Average Interruption Frequency Index: (PEAIFI)

PEAIFI will give the average frequency of critical equipment interruption per critical equipment over a predefined period. The objective of this index is to show the number of average interruption of critical equipment in the plant. PEAIFI can be defined with the following equation:

$$PEAIFI = \frac{Total\ Number\ of\ Critical\ Equipment\ Interrupted}{Total\ Number\ of\ Critical\ Equipment\ Connected}$$

$$PEAIFI = \frac{\sum CEI}{\sum CEC} \qquad (3.1)$$

The total number of critical equipment interrupted can be defined as the total number of equipment that would affect the plant production if interrupted. The total number of critical equipment connected can be defined as the total number of equipment that would affect the plant product if interrupted.

The existing index, ASIFI is based on the kVA of the equipment regardless of the type of the load that may or may not shut down the plant. The ASIFI value will be changed if kVA rating of the tripped equipment is changed, while the plant is interrupted for the same duration. Proposed PEAIFI relates with the interrupted critical equipment.

The lower limit for this index is zero when there is no interruption while there is no higher limit for this index. This index, with the help of other indices, will show the evaluation of the whole plant. This is a dimensionless index.

3.3 Plant Individual Equipment Average Interruption Frequency Index: (PIEAIFI)

PIEAIFI is the average frequency of individual critical equipment interruption per critical equipment over a predefined period. The objective of this index is to show the total average number of critical individual equipment interruption in the plant. PIEAIFI can be defined with the following equation:

$$PIEAIFI = \frac{Total\ Number\ of\ Individual\ Critical\ Equipment\ Interrupted}{Total\ Number\ of\ Critical\ Equipment\ Connected}$$

$$PIEAIFI = \frac{\sum ICEI}{\sum CEC} \qquad (3.2)$$

The total number of individual equipment interrupted can be defined as the total number of individual equipment that would affect the plant product if interrupted. So, if there is any equipment interrupted twice will be counted only one time while in PEIFI will be counted twice. The total number of equipment connected can be defined as the total number of equipment connected that would affect the plant product if interrupted.

The lower limit for this index is zero when there is no interruption while the higher limit for this index is one when all the equipment in the plant is interrupted. This index is dimensionless index.

3.4 Plant Average Interruption Frequency Index: (PAIFI)

The PAIFI will give the average frequency of the plant interruption per critical equipment over a predefined period. The objective of this index is to show how many, in average, the plant interrupted per critical equipment. The equation can be defined as follows:

$$PAIFI = \frac{Total\ Number\ of\ Plant\ Interruptions}{Total\ Number\ of\ Critical\ Equipment\ Connected}$$

$$PAIFI = \frac{\sum PI}{\sum CEC} \tag{3.3}$$

The total number of plant interruptions can be defined as the total number of plant shut down due to the interruption of critical equipment. The total number of critical equipment connected can be defined as the total number of critical equipment that would affect the plant production if interrupted.

The lower limit for this index is zero when there is no interruptions while there is no higher limit for this index. This index is a dimensionless index.

The difference between PEAIFI and PAIFI is that the PEAIFI gives an average frequency of the critical equipment interruptions while PAIFI deals with the number of interruptions for the whole plant.

3.5 Plant Average Interruption Duration Index: (PAIDI)

The PAIDI will give the average plant interruption duration per critical equipment over a predefined period. The objective of this index is to show the average hours the plant was interrupted per critical equipment.

$$PAIDI = \frac{\begin{array}{l}\textit{Total Critical Equipment Interruption Duration} + \textit{Number of Plant Interruptions} \\ \times \textit{Plant Restartup Duration}\end{array}}{\textit{Total Number of Critical Equipment Connected}}$$

$$PAIDI = \frac{\sum CEID + \sum PI \times PSD}{\sum CEC} \qquad (3.4)$$

The total critical equipment interruptions duration can be defined as the summation of the equipment interruption period from the minute the equipment tripped until the minute the equipment returned to service. Number of plant interruptions can be defined as the total number the plant Shutdown due to a failure of critical equipment. Plant re-start up time is the time that the plant needs to be back in service. There re-start up time differs from plant to plant. Due to this, the re-start up time is very important in determining the duration of the plant shutdown. The duration of the critical equipment shutdown alone is not enough for the industrial plant calculation. The total number of critical equipment connected can be defined as the total number of critical equipment that would affect the plant if interrupted.

The existing index, ASIDI is based on the kVA of the equipment regardless of the type of the load that may or may not shut down the plant. The ASIDI value will be changed if kVA rating of the tripped equipment is changed, while the plant is interrupted for the same duration. The restart up time is not considered in the existing ASIDI index which makes a significant difference between the plants interruption durations. Proposed PAIDI considers the plant restart up time and the interrupted critical equipment duration.

The lower limit for this index is zero when there is no interruption while there is no higher limit for this index. The unit for this index is hours.

3.6 Plant Average Availability Index;(PAAI)

PAAI can be defined, as the plant availability percentage in one year.

The objective of this index is to show how much in average the plant is available per year in percentage.

Average plant availability index in a year can be calculated by the following index:

$$PAAI = \frac{\begin{array}{l}(8760 - \mathit{Total\,Critical\,Equipment\,Interruption\,Duration} + \mathit{Number\,of\,Plant\,Interruptions} \\ \times \mathit{Plant\,Restartup\,Duration}) \times 100\end{array}}{8760}$$

or,

$$PAAI = \frac{(8760 - \mathit{Total\ Critical\ Equipment\ Connected} \times PAIDI) \times 100}{8760}$$

$$PAAI = \frac{(8760 - \sum CEC \times PAIDI) \times 100}{8760} \qquad (3.5)$$

The existing index, ASAI is based on the kVA of the equipment regardless of the type of the load that may or may not shut down the plant. The ASAI value will be changed if kVA rating of the tripped equipment is changed, while the plant is interrupted for the same duration. The PAAI relates with the interrupted critical equipment. The restart up time is not considered in the existing ASAI index which makes a significant difference between the plants interruption durations. Proposed PAAI considers the plant restart up time and the interrupted critical equipment duration.

The lower limit for this index is zero while the higher limit for this index is 100. The unit for this index is percentage.

3.7 Plant Shutdown Cost index: (PSCI)

Plant Shutdown cost index can be defined as the loss of cost due to plant interruption in a pre-defined period. The objective of this index is to show how much the plant Shutdown will cost.

$$PSCI = \textit{Plant production Cost Per Hour} \times (\textit{Total Critical Equipment Interruption Duration} \\ + \textit{Number of Plant Interruptions} \times \textit{Plant} \text{ Re}\textit{startup Duration})$$

$$PSCI = PPC \times (\sum CEID + \sum PI \times PSD) \tag{3.6}$$

The plant product cost is the plant income in an hour from selling the plant product.

The total critical equipment interruption duration can be defined as the summation of the equipment interruption period from the time the equipment trips until the time the equipment is returned to service. The number of plant interruptions can be defined as the total number the plant Shutdown due to a failure of critical equipment. Plant re-start up time is the time that the plant needs to be back in service.

The lower limit for this index is zero when there is no interruption in the plant while there is no higher limit for this index. It differs from a plant to a plant. If the plant Shutdown cost is high then there is a need to study the need for upgrading the plant power. However, if the plant shutdown cost is low then there is no need to upgrade the plant supply system. The unit for this index is dollars. What defines the high and low cost is the plant annual cost saving index that helps the plant management to decide whether the plant power upgrading is required or not.

3.8 Plant annual Cost saving index: (PACSI)

PACSI will show the plant saving cost annually. This will help the plant management and engineers to select the best upgrading option. This can be defined by the following equation:

$$PACSI = ((PSCI\ before\ Modification - PSCI\ After\ Modification) + (Plant\ Maintenance\ Cost\ before\ Modification - Plant\ Maintenance\ Cost\ after\ Modification) - Annual\ Investment\ of\ Equipment\ Yearly$$

$$PACSI = ((PSCBM - PSCAM) + (PMCBM - PMCAM)) - AIOEY \tag{3.7}$$

PSCI before modification can be defined as the cost of the existing plant Shutdown that been calculated using equation (3.6). PSCI after the modification can be defined as the cost of the Upgraded plant Shutdown that been calculated using equation (3.6). Maintenance cost before the modification is defined as how much money was spent in this plant to maintain it yearly. Maintenance cost after the modification can be defined as the cost that will be spend on the plant after the new modification yearly. New Annual Correlated equipment modification cost is the plant power supply upgrading cost including the cost for material and manpower divided by the service life of the new equipment.

Although some plants having high PAAI, the saving cost justifies the plant power upgrading. On the other hand, other plants with low level of PAAI can not be justified. Different upgrading options can be evaluated using this index.

The lower limit for this index is in negative when there is money loss if certain upgrading option selected while there is no higher limit for this index. The unit of this index is Dollar.

Chapter 4

COMPARISION BETWEEN THE EXISTING AND THE PROPOSED INDICES

4.1 Introduction

In this chapter, the existing reliability indices are evaluated based on the non-critical loads, the effect of changing the KVA rating and the plant re-startup time. The effect of considering non-critical loads in the existing reliability indices is studied and compared to the proposed industrial plant reliability indices. The difference in the existing reliability indices by changing the load KVA rating is studied in this chapter. The need for the plant re-startup time and difference in the proposed reliability indices when changing the plant re-startup time duration is also studied.

4.2 Non Critical Loads

Figure 4.1 shows a single line diagram of a single ended Bus-bar (SE) called BB01. A single ended bus-bar is a bus-bar with one main breaker feeding the connected equipment to it. Twelve different equipment listed in BB01 are fed from the main breaker MB1. Among those equipment G1, G4, G5, G8, G9, G100 are main pumps without spare. If any of these pumps trips, the plant will be shut down. G6A, G6B, G7A and G7B are main pumps with spare. If any of these pumps trips, the spare pump will take over. The plant will be shut down only if both are trip at the same time. Other equipment, Lighting Panel (LP) and Air Handling Unit (AHU) will not cause the plant to shut down.

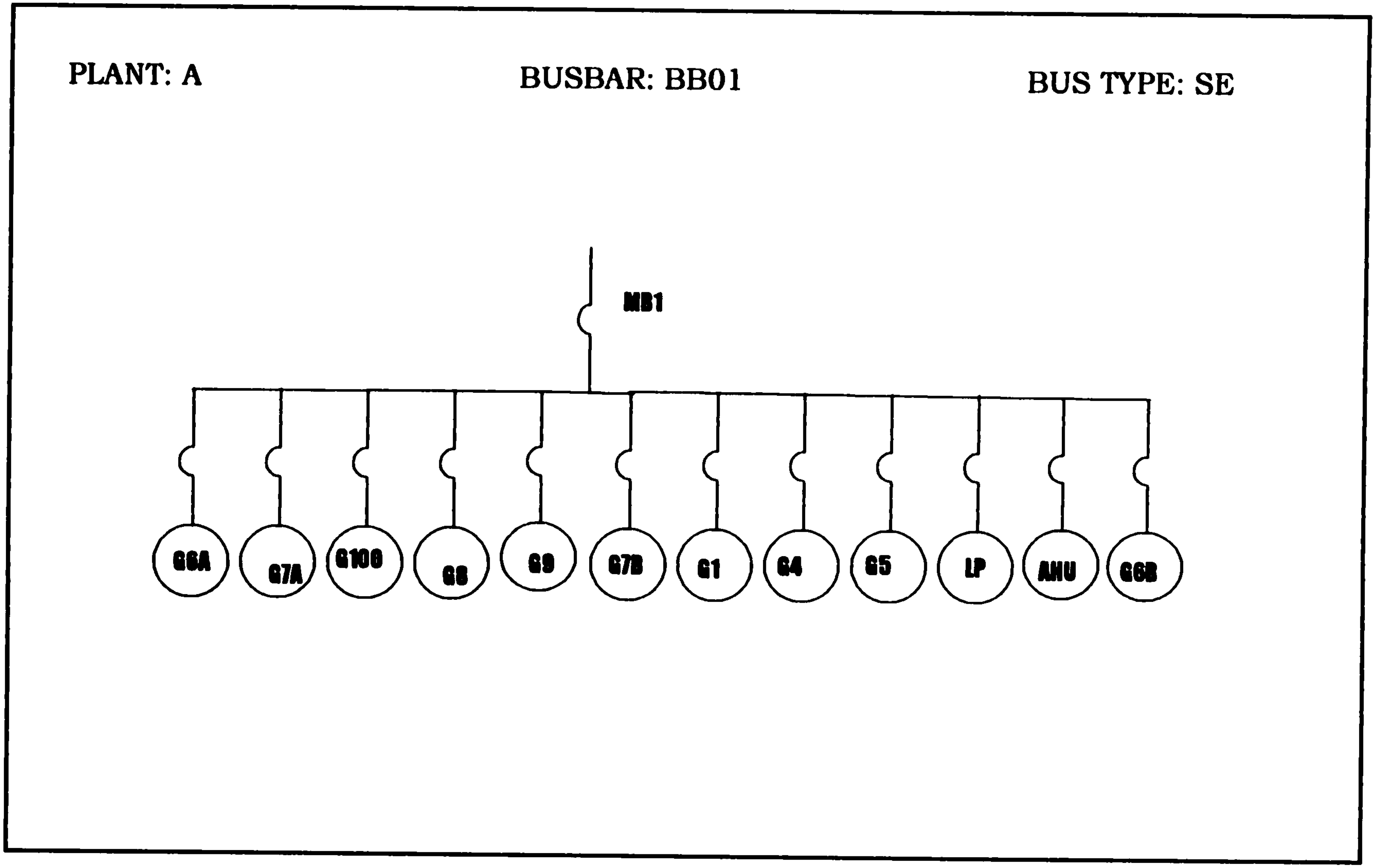


Figure 4.1: Single Line Diagram BB01

Table 4.1 is the equipment table of the plant. It shows the connected equipment to BB01 with their KVA rating and load type. The load type for the main pump is denoted by M. The load type for the main pump that has spare is denoted by MA. The spare pump is denoted by SP. The main breaker is denoted by MB. These classification were used to segregate the different load types in the software that calculates the Industrial Plant Reliability Indices as shown in appendix A.

To study the effect of the non-critical loads in the existing and proposed indices, different non-critical equipment were listed in Table 4.2. Table 4.2 shows the interrupted equipment with their KVA rating, the bus-bar interruption duration, the KVA interruption duration, the bus bar interruption start date and the bus-bar interruption finish date.

Table 4-1: Existing indices Non Critical Load Equipment Table

Sl. No.	Equipment	KVA	Load Type
1	G6A	100	MA
2	G7A	100	MA
3	G100	12	M
4	G8	10	M
5	G9	10	M
6	G7B	100	SP
7	G1	10	M
8	G4	12	M
9	G5	10	M
10	LP	15	LP
11	AHU	30	AHU
12	G6B	100	SP
13	MB1	0	MB
Total		509	

Table 4-2: Existing Indices Non Critical Load Bus-bar Interruption Table

Sl. No.	Interrupted Equipment	Interrupted KVA	Bus-bar Interruption Duration	KVA Interruption Duration	Bus-bar Interruption Start Date	Bus-bar Interruption Finish Date
1	G6A	100	99.05	9905	01/01/01 2:02 Hr	01/05/01 5:05 Hr
2	AHU	30	72.67	2180.1	01/01/01 12:20 Hr	01/04/01 13:00 Hr
3	G7A	100	106	10600	05/14/01 12:00 Hr	05/18/01 22:00 Hr
4	LP	15	93	1395	06/16/01 01:00 Hr	06/19/01 22:00 Hr
5	G6A	100	52.5	5250	06/16/01 19:00 Hr	06/18/01 23:30 Hr
Total		345	423.22	29330.1		

The equipment listed in table 4.2 are G6A, which have been interrupted twice, G7A, AHU and LP. It is noticed that all these equipment are considered as non-critical loads, since the spare pumps G6B and G7B takes over when G6A and G7A are interrupted. The AHU and LP will never shut down the plant if tripped. The total KVA interrupted in this bus bar is 345 KVA. The bus-bar interruption duration is 423.22 hours. The total KVA interruption duration is 29330.1 hours. The total connected KVA is 509KVA.

Based on the data mentioned in table 4.2, the existing reliability indices have been calculated in table 4.3 which shows ASIFI, ASIDI and APAI. Using the same data in the proposed industrial plant reliability indices it was found that all the proposed indices were zero except the APAI, which was 100. This shows that the existing indices vary based on non critical loads that did not affect the plant production when tripped.

Table 4-3 : Non Critical Loads Bus-bar Existing Reliability Indices

ASIFI	ASIDI	APAI
0.68	57.62	99.34

This data clearly concludes that the existing reliability indices can not show the actual plant condition and might led to an inaccurate figure of the plant reliability.

4.3 Loads with different KVA ratings.

Fig 4.2 shows a single line diagram of a double ended normally open tie breaker Bus-bar (DENO) called BB02. A double ended bus-bar is a bus-bar with two main breakers feeding the equipment connected to the bus-bar along with normally open tie breaker that will close when one of the main breakers is tripped.

In order to study the effect of changing the KVA rating while keeping the same interruption duration, eleven equipment are listed in Table 4-4 with their KVA ratings.

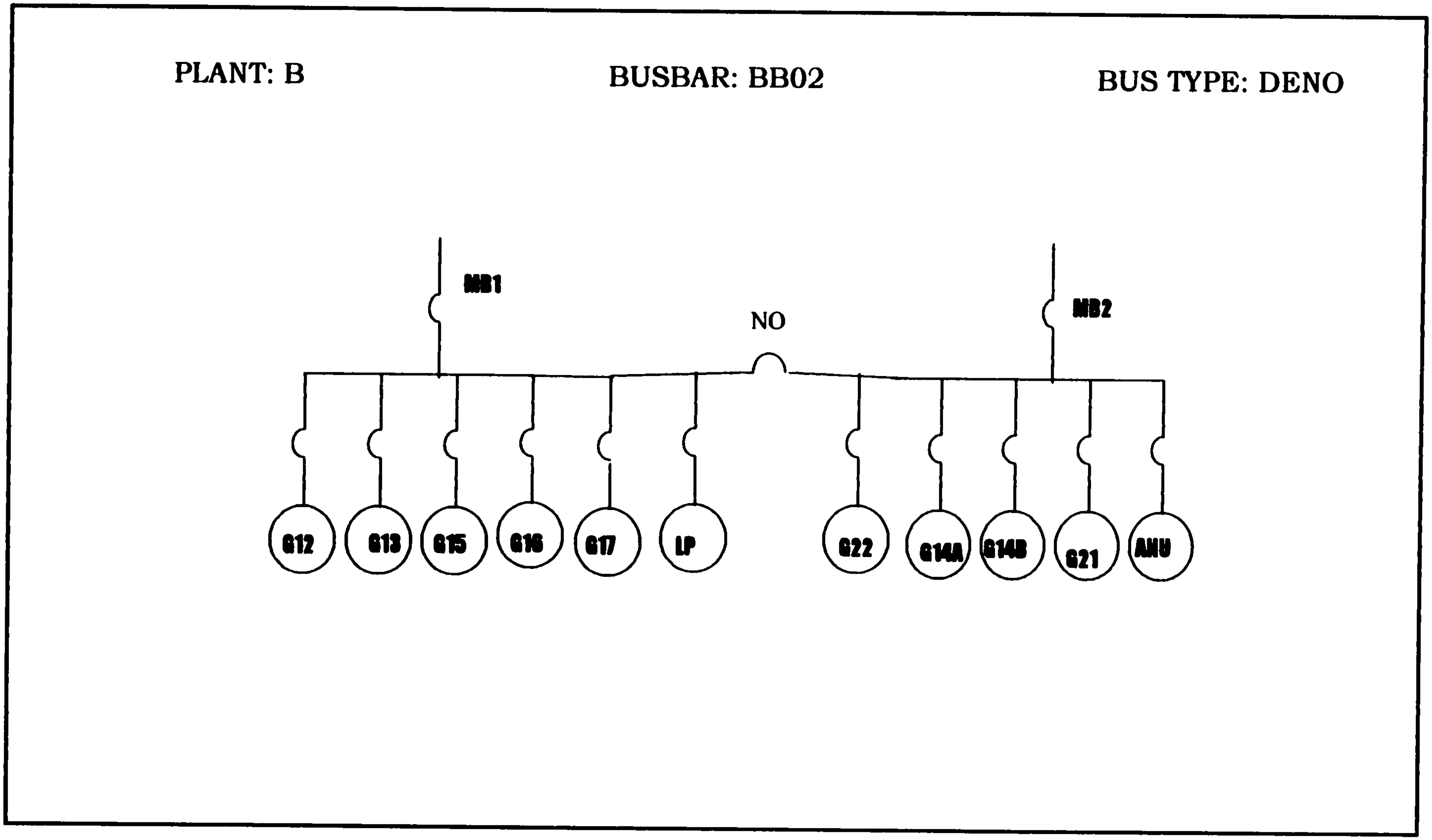


Figure 4.2: Single Line Diagram BB02

Table 4-4 : Existing Indices Loads with different KVA Equipment Table.

Sl. No.	Equipment	KVA	Load Type
1	G12	12	M
2	G22	10	M
3	G13	10	M
4	G14A	12	MA
5	G14B	12	SP
6	G15	10	M
7	G16	10	M
8	G17	500	M
9	G21	14	M
10	LP	15	LP
11	AHU	15	AHU
12	MB1	0	MB
13	MB2	0	MB
14	TIE	0	MB
Total		620	

To study the effect of change in KVA rating in the existing and proposed reliability indices, G17 was selected to trip thrice with 500 KVA rating. Table 4-5 shows the interrupted equipment with their KVA rating, the bus-bar interruption duration, the KVA interruption duration, the bus bar interruption start date and the bus-bar interruption finish date.

Table 4-5: Existing Indices Before Changing the Load KVA rating Bus-bar Interruption Table

Sl. No.	Interrupted Equipment	Interrupted KVA	Bus-bar Interruption Duration	KVA Interruption Duration	Bus-bar Interruption Start Date	Bus-bar Interruption Finish Date
1	G17	500	2.17	1085	04/18/01 20:50 Hr	04/18/01 23:00 Hr
2	G17	500	246	123000	06/18/01 11:00 Hr	06/28/01 17:00 Hr
3	G17	500	5	2500	08/02/01 11:00 Hr	08/02/01 16:00 Hr
Total		1500	253.17	126585		

Based on the data mentioned in table 4-5, the existing reliability indices have been calculated in table 4-6 which shows ASIFI, ASIDI and APAI. This data is based on 500 KVA rating for G17.

Table 4-6 : Before Changing the Load KVA rating Bus-bar Existing Reliability Indices

ASIFI	ASIDI	APAI
2.42	204.17	97.67

By changing the KVA rating for G17 to 10 KVA instead 500KVA and changing the KVA rating for G22 to 500KVA instead of 10KVA and repeating the same calculation the bus-bar interruption table will be as shown in table 4-7.

Table 4-7: Existing Indices After Changing the Load KVA rating Bus-bar Interruption Table

Sl. No.	Interrupted Equipment	Interrupted KVA	Bus-bar Interruption Duration	KVA Interruption Duration	Bus-bar Interruption Start Date	Bus-bar Interruption Finish Date
1	G17	10	2.17	21.7	04/18/01 20:50 Hr	04/18/01 23:00 Hr
2	G17	10	246	2460	06/18/01 11:00 Hr	06/28/01 17:00 Hr
3	G17	10	5	50	08/02/01 11:00 Hr	08/02/01 16:00 Hr
Total		30	253.17	2531.7		

Based on the changes, the existing reliability indices have been calculated in table 4-8 which shows ASIFI, ASIDI and APAI. This data is based on 10 KVA rating for G17.

Table 4-8 : Before Changing the Load KVA rating Bus-bar Existing Reliability Indices

ASIFI	ASIDI	APAI
0.05	4.08	99.95

From this case it can be seen that the APAI, ASIDI and ASIFI have changing based on the KVA load while the plant interruption duration is fixed. This shows that the reliability indices are controlled by the KVA rating while it should be controlled by the plant interruption duration regardless of the KVA load. Using the KVA load to evaluate the industrial plant will not give a clear picture of the plant reliability and would vary for a same plant by changing a load KVA rating.

4.4 Plant re-startup time.

The existing reliability indices don't consider the plant re-startup time. The same equipment listed in figure 4.2 and table 4.4 were used to study the effect of changing the plant re-startup time duration in the proposed reliability indices calculation. As it can be noticed that there are eight critical equipment in Bus-bar BB02, which are G12, G22, G13, G15, G16, G17, G21 and G14A or G14B. The main and spare pump G14A and G14B respectively are considered as single equipment. The proposed reliability indices bus-bar interruption table, are shown in Table 4-9. It shows the interrupted equipment, number of plant interruptions, number of equipment interrupted, the bus-bar interruption duration, the bus bar interruption start date and the bus-bar interruption finish date.

Table 4-9: Proposed Reliability Indices Bus-bar Table

Sl. No.	Interrupted Equipment	Number of Bus-bar Interruption	Number of equipment interruption	KVA Interruption Duration	Bus-bar Interruption Start Date	Bus-bar Interruption Finish Date
1	G17	1	1	2.17	04/18/01 20:50 Hr	04/18/01 23:00 Hr
2	G17	1	1	246	06/18/01 11:00 Hr	06/28/01 17:00 Hr
3	G17	1	1	5	08/02/01 11:00 Hr	08/02/01 16:00 Hr
Total		3	3	253.17		

In order to observe the difference in the proposed reliability indices two different re-startup times were studied. Using the data mentioned in table 4-9 with 0 hours plant re-startup duration and 200,000 dollar production cost per hour, the proposed industrial plant reliability indices are listed in Table 4-10.

Using the data mentioned in table 4-9, with 15 hours plant re-startup duration and 200,000 dollar production cost per hour, the proposed industrial plant reliability indices are listed in Table 4-11.

Table 4-10 : Proposed Industrial Plant Reliability Indices With 0 hours Re-startup time.

PEAFI	PIEAFI	PAIFI	PAIDI	PAAI	PSCI
0.38	0.13	0.38	31.65	97.11	2109750

Table 4-11 : Proposed Industrial Plant Reliability Indices With 15 hours Re-startup time.

PEAFI	PIEAFI	PAIFI	PAIDI	PAAI	PSCI
0.38	0.13	0.38	37.27	96.60	2484750

When the re-startup duration changed from zero to 15 hours, the PSCI increased from $2,109,750 to $2,484,750, the PAAI decreased from 97.11 to 96.6 and PAIDI increased from 31.65 to 37.27 hours. Therefore, the different plants re-startup time duration is a major factor in the Plant Reliability Evaluation.

Chapter 5

Evaluation of proposed Reliability indices through case studies

5.1 Introduction

In order to show the variance in the industrial plants reliability indices before and after re-arranging the loads, plant called A with three different bus bars BB01, BB02 and BB03. Different equipment were studied in this chapter. This chapter is divided into three sections, the first section shows detail calculation of the industrial plant reliability indices before arranging the loads, the second section shows the plant reliability indices after arranging the loads and the third section are the conclusion drawn out of the comparison between the two cases.

5.2 Proposed industrial plant reliability indices before arranging the loads

Fig 5.1 shows a single line diagram of a Single Ended Bus-bar (SE) called BB01. A SE bus-bar is a bus-bar with one main breaker feeding the connected equipment to it. Fourteen different equipment listed in BB01 are fed from the main breaker MB1. Among those equipment G1, G2, G3, G4, G8, G9 are main pumps without spare. If any of these pumps trips, the plant will be shut down. G6A, G6B, G7A and G7B are main pumps with spare. If any from these pumps trips the spare pump will take over. The plant will be shut down only both pumps are tripped at the same time. Other equipment, Lighting Panel LP1and LP2 and Air Handling Unit AHU1 and AHU2 will not cause the plant to shut down.

Fig 5.2 shows a single line diagram of a Double Ended Normally Opened tie breaker Bus-bar (DENO) called BB02. A DENO tie breaker bus-bar is a bus-bar with two main breakers feeding the equipment connected to the bus-bar along with normally open tie breaker that will close when one of the main breakers is tripped. Fourteen different equipment listed in BB02 are fed from the two main breakers MB1and MB2. Among those equipment G15, G16, G19, G20, G21, G22 are main pumps without spare. If any from these pumps trips, the plant will be shut down. G14A, G14B, G17A and G17B are main pumps with spare. . If any from these pumps trips the spare pump will take over. The plant will be shut down only both pumps are tripped at the same time. Other equipment, Lighting Panel LP3and Air Handling Unit AHU3 will not cause the plant to shut down.

Fig 5.3 shows a single line diagram of a double ended normally closed tie breaker Bus-bar (DENC) called BB03. A DENC tie-breaker bus bar is a bus-bar with two main breakers feeding the equipment connected to the bus-bar along with normally closed tie breaker. Sixteen different equipment listed in BB03 are fed from the two main breakers MB1and MB2. Among those equipment G28, G30, G31, G32, G34, G40 are main pumps without spare. G23A, G23B, G24A, G24B, G25A and G25B are main pumps with spare. Other equipment, Lighting Panel LP4, LP5 and Air Handling Unit AHU4, AHU5 will not cause the plant to shut down.

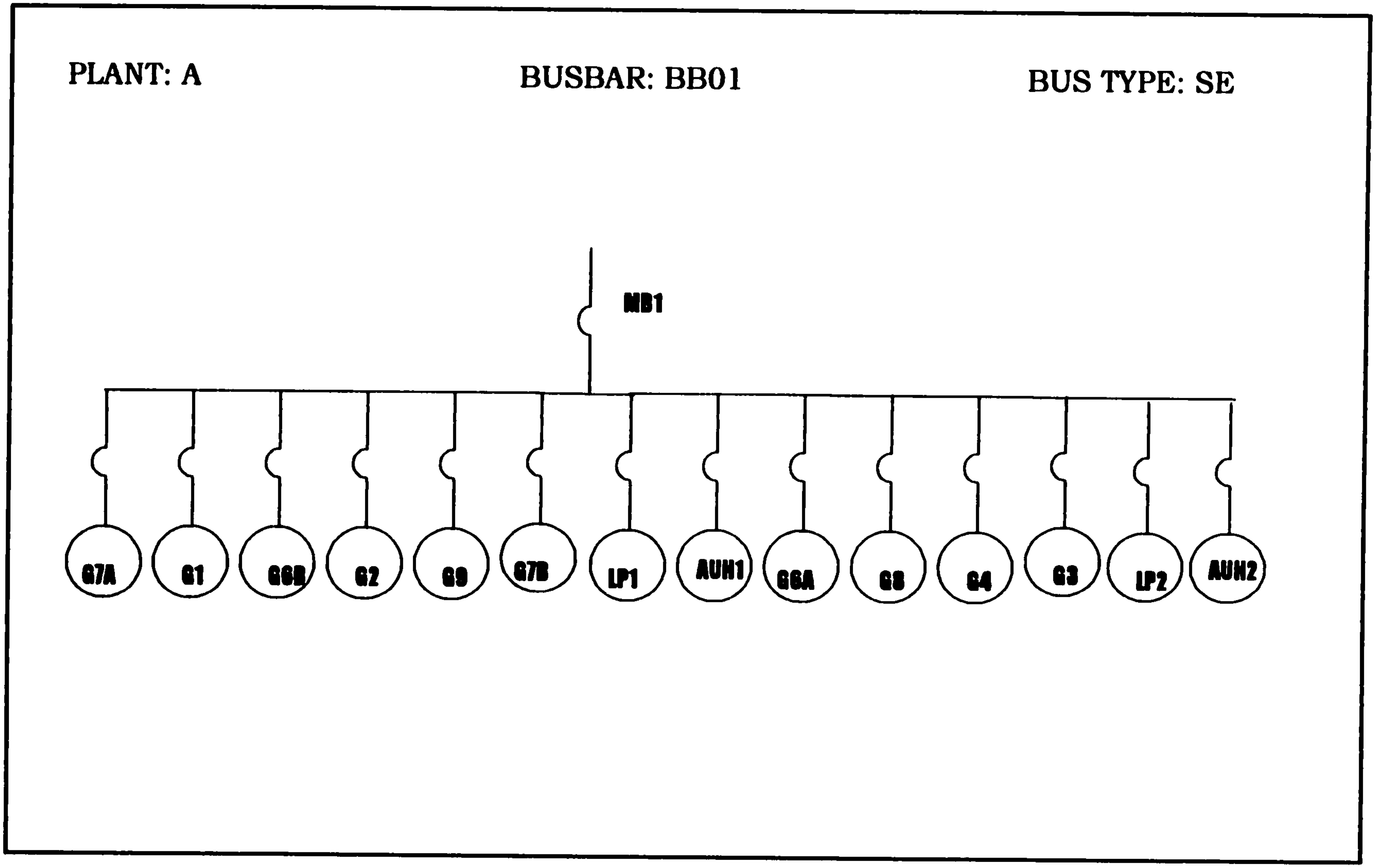


Figure 5.1: Single Line Diagram BB01 Before arranging the load

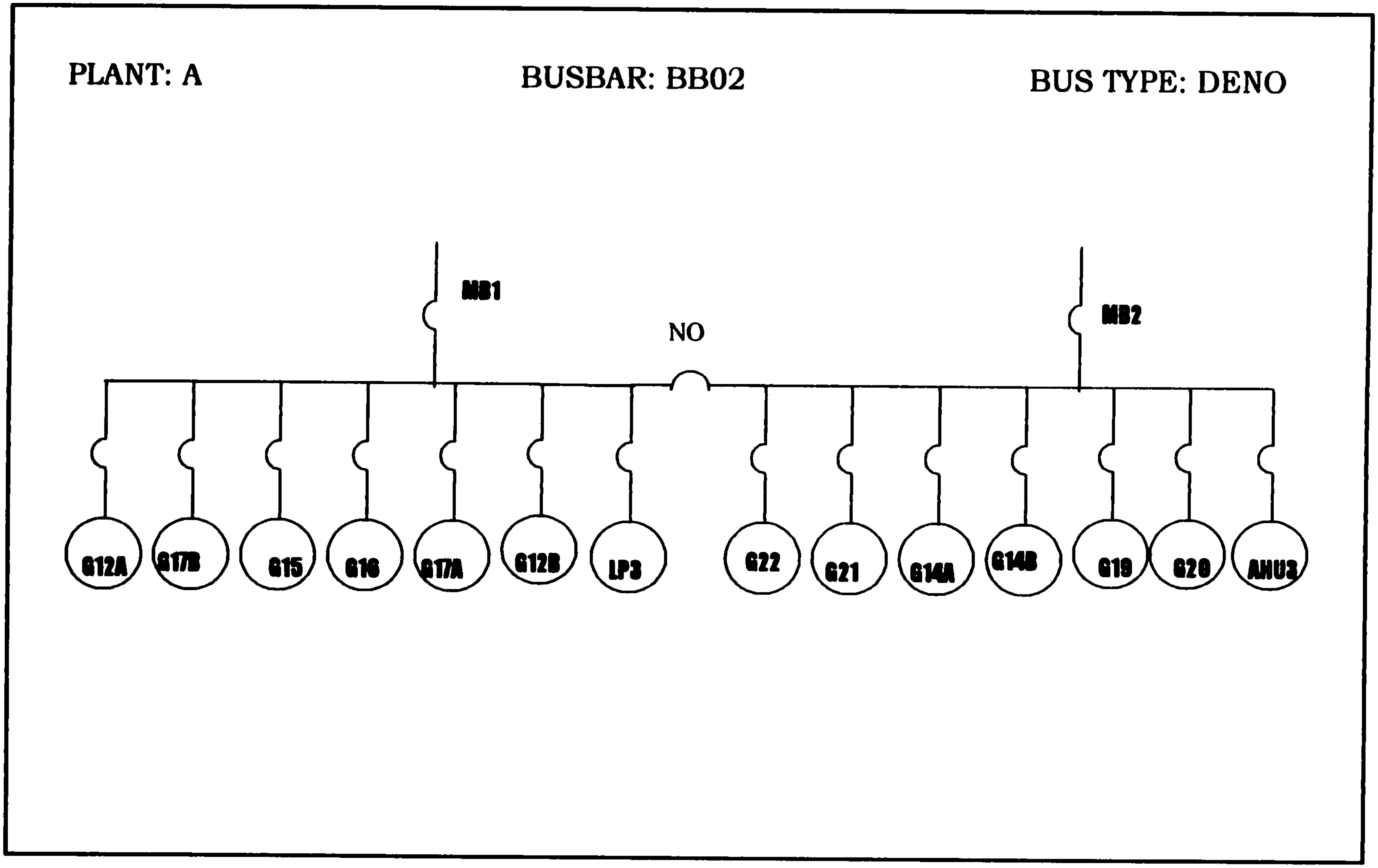


Figure 5.2: Single Line Diagram BB02 before aranging the loads

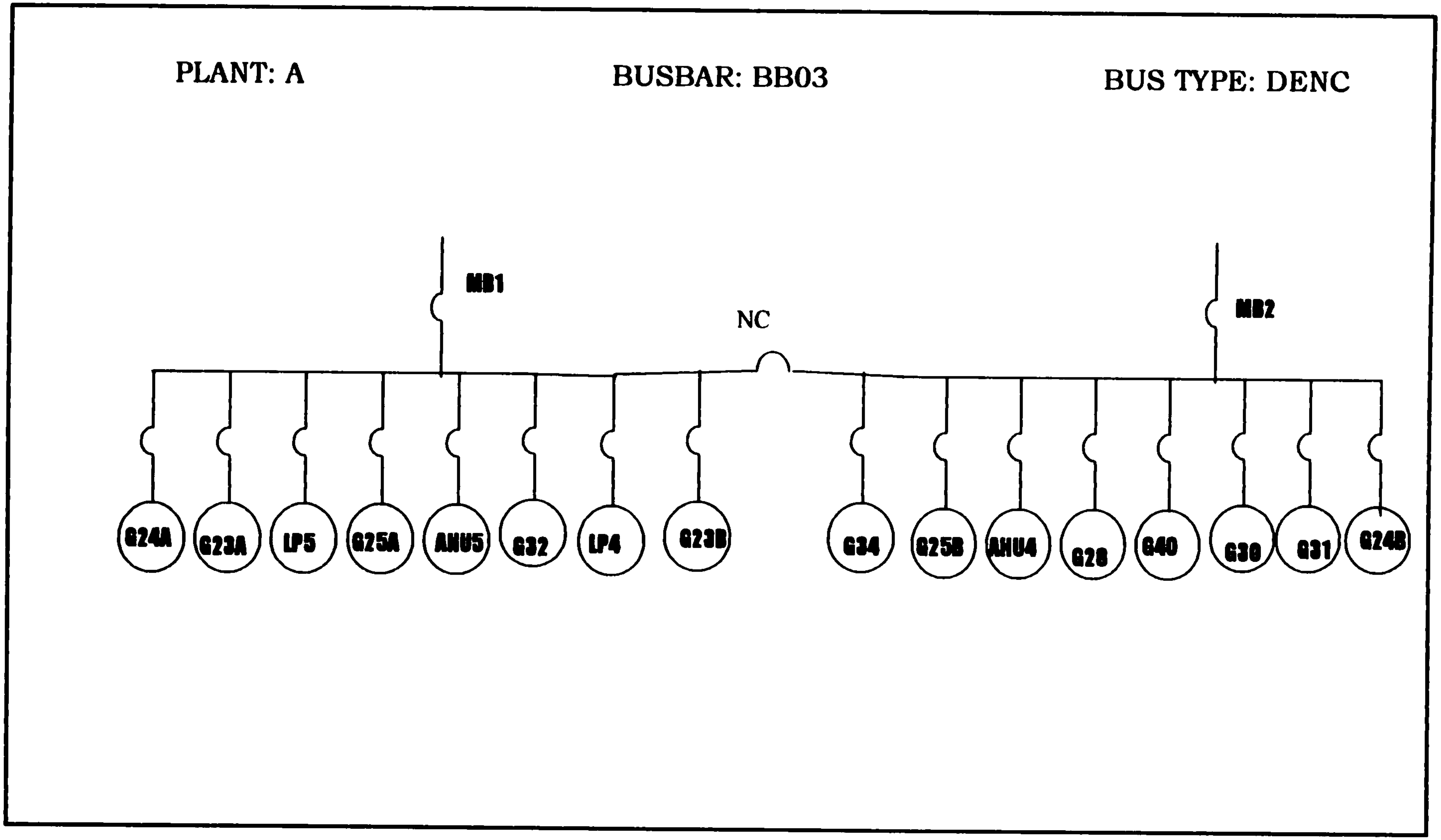


Figure 5.3: Single Line Diagram BB03 before arranging the load

Table 5.1 shows the plant interrupted equipment, the bus bar of the interrupted equipment and the equipment interruption duration start and finish times. The interrupted equipment in all the three bus bars listed in this table with their interruption duration in order to calculate the industrial plant reliability indices.

Table 5-1: Interruption Data for Plant A

No.	Bus bar number	Interrupted Equipment	Interruption start Time	Interruption Finish Time
1	BB01	AHU2	05/09/01 7:00 Hr	05/09/01 23:00 Hr
2	BB01	G1	05/14/01 12:00 Hr	05/14/01 13:00 Hr
3	BB01	G6A	01/01/01 2:02 Hr	01/01/01 5:05 Hr
4	BB01	G7A	03/03/01 11:00	03/03/01 12:30 Hr
5	BB01	G7B	01/01/01 1:01	01/01/01 3:01 Hr
6	BB01	LP1	06/16/01 20:00 Hr	06/16/01 22:00 Hr
7	BB01	MB1	06/16/01 19:00 Hr	06/17/01 23:30 Hr
8	BB02	G14A	06/18/01 12:00 Hr	06/18/01 14:00 Hr
9	BB02	G15	06/18/01 11:00 Hr	06/18/01 13:00 Hr
10	BB02	MB1	06/16/01 4:00 Hr	06/16/01 21:00
11	BB02	MB2	06/16/01 10:50	06/16/01 23.00
12	BB03	G23A	08/02/01 11:00 Hr	08/02/01 13:00 Hr
13	BB03	G34	06/18/01 20:50 Hr	06/18/01 21:00 Hr
14	BB03	G40	01/01/01 12:20 Hr	01/01/01 13:00 Hr
15	BB03	MB1	09/09/01 12:30 Hr	09/09/01 15:00 Hr
16	BB03	MB2	09/09/01 12:00 Hr	09/09/01 14:00 Hr
17	BB03	MB2	09/02/01 1:02 Hr	09/02/01 3:02 Hr

Table 5.2 is the bus bar interruption table before arranging the plant loads for B001 which shows the critical interrupted equipment, the number of equipment interruption, bus bar interruption duration, the bus bar interruption start and finish times. The bus bar interruption duration is the difference between the bus bar interruption start and finish time in hours. It can be seen that the only critical equipment interrupted in B001 is G1 which led to one plant interruption. The main breaker is also considered critical which led to another plant interruption and since B001 is single ended bus bar all the eight critical equipment connected to the bus bar have been interrupted.

Table 5-2: BBO1 Interruption Table before arranging the loads

No.	Equipment Interrupted	Number Of Bus bar Interruption	Number of equipment interruption	Bus bar Interruption Duration	Bus bar Interruption starting Time	Bus bar Interruption Finishing time
1	G1	1	1	1	05/14/01 12:00 Hr	05/14/01 13:00 Hr
2	MB1	1	8	28.5	06/16/01 19:00 Hr	06/17/01 23:30 Hr
TOTALS		2	9	29.5		

Table 5.3 is the bus bar interruption table before arranging the plant loads for B002. It can be seen that the only critical equipment interrupted in B002 is G15 which led to one plant interruption. As it can be seen there is common interruption duration between MB1 and MB2 which led to plant interruption so, all the nine critical equipment connected the bus bar been interrupted.

Table 5-3: BBO2 Interruption Table before arranging the loads

No.	Equipment Interrupted	Number Of Bus bar Interruption	Number of equipment interruption	Bus bar Interruption Duration	Bus bar Interruption starting Time	Bus bar Interruption finishing Time
1	MB1_MB2	1	9	10.17	06/16/01 10:50 Hr	06/16/01 21:00 Hr
2	G15	1	1	2	06/18/01 11:00 Hr	06/18/01 13:00 Hr
TOTAL		2	10	12.17		

Table 5.4 is the bus bar interruption table before arranging the plant loads for B003. It can be seen that there are two critical equipments interrupted in B003 which are G34, G40 that led to one plant interruption. As it can be seen there is common interruption duration between MB1 and MB2 which led to plant interruption so, all the nine critical equipment connected the bus bar have been interrupted.

Table 5-4: BBO3 Interruption Table before arranging the loads

No.	Equipment Interrupted	Number Of Bus bar Interrup-tion	Number of equipment interruption	Bus bar Interruption Duration	Bus bar Interruption starting Time	Bus bar Interruption Finishing Time
1	G40	1	1	0.67	01/01/01 12:20 Hr	01/01/01 13:00 Hr
2	G34	1	1	0.17	06/18/01 20:50 Hr	06/18/01 21:00 Hr
3	MB1_MB2	1	9	1.5	09/09/01 12:30 Hr	09/09/01 14:00 Hr
TOTALS		3	11	2.34		

Table 5.5 is the plant interruption table before arranging the plant loads which shows the interrupted bus bar, the number of plant interruptions, plant interruption duration, the plant interruption start and finish times. The function of this table is to combines the common interruption durations between the plant bus bars. As it can be noticed that there is a common duration between B002 and B001 which is considered as one plant interruption even though the two bus bars are interrupted.

Table 5-5: Plant Interruption Table before arranging the loads

No	Bus bars Interrupted	Number of Plant Interruptions	Plant Interruption Durations	Plant Interruption starting time	Plant Interruption Finishing Time
1	BB03	1	0.67	1/1/2001 12:20:00 PM	1/1/2001 1:00:00 PM
2	BB01	1	1	5/14/2001 12:20:00 PM	5/14/2001 1:00:00 PM
3	BB02, BB01	1	36.67	6/16/2001 10:50:00 AM	6/17/2001 11:30:00 PM
4	BB02	1	2	6/18/2001 11:00:00 AM	6/18/2001 1:00:00 PM
5	BB03	1	0.17	6/18/2001 8:50:00 AM	6/18/2001 9:00:00 PM
6	BB03	1	1.5	9/9/2001 12:30:00 PM	9/9/2001 2:00:00 PM
TOTALS		6	42.01		

Table 5.6 summarizes the industrial plant reliability data before arranging the loads in order to us it in the industrial plant reliability indices calculation. Table 5.6 shows the total equipment connected in the plant, total individual equipment interrupted in the plant, total equipment interrupted in the plant, total plant interruptions and total plant interruption duration.

Table 5.7 shows the industrial plant reliability indices for plant A before arranging the load. These indices calculated by using the data mentioned in table 5.6 and the industrial plant reliability indices equations mentioned in chapter 4. The plant re-startup time assumed is to be 3 hours. The plant production cost per hour is assumed to be $500, 000 and the investment of the new equipment for that year is $2MM. The plant shut down cost after the modification is assumed to be $500,000. The maintenance cost before the modification is assumed to be $750,000 and after the modification to be $500,000.

Table 5-6: Reliability summary data before arranging the loads

Total Equipment Connected	Total Individual Equipment Interrupted	Total Equipment Interrupted	Total plant Interruptions	Total plant Interruptions Duration
26.00	26.00	30.00	6.00	42.01

Table 5-7: Industrial Plant Reliability indices before arranging the loads

PEAIFI	PIEAFI	PAIFI	PAIDI	PAAI	PSCI	PACSI
1.15	1.00	0.23	2.31	99.31	1,250,208.33	3,001,041.67

5.3 Proposed industrial plant reliability indices after arranging the loads

Fig 5.4 shows a single line diagram of a single ended Bus-bar (SE) called BB01 after arranging the loads. Fourteen different equipments listed in BB01 are fed from the main breaker MB1. Among those equipment G6B, G7B, G12B, G14B, G17B, G23B, G24B and G25B are spare pumps. If any from these pumps trips the spare pump will take over. The plant will be shut down only both pumps are tripped at the same time. Other equipment, Lighting Panel LP1, LP2 and LP5 and Air Handling Unit AHU1, AHU2 and AHU4will not cause the plant to shut down.

Fig 5.5 shows a single line diagram of a double ended normally open tie breaker Bus-bar (DENO) after re-arranging the loads called BB02. Fourteen different equipments listed in BB02 are fed from the two main breakers MB1and MB2. Among those equipment G8, G15, G16, G19, G20, G21, G22 are main pumps without spare. If any from these pumps trips, the plant will be shut down. G6A, G7A, G12A,G14A and G17A are main pumps with spare. If any from these pumps trips the spare pump will take over. The plant will be shut down only both pumps are tripped at the same time.

Other equipment, Lighting Panel LP3 and Air Handling Unit AHU3 will not cause the plant to shut down.

Fig 5.6 shows a single line diagram of a double ended normally closed tie breaker Bus-bar (DENC) after re-arranging the loads called BB03. Sixteen different equipments listed in BB03 are fed from the two main breakers MB1and MB2. Among those equipment G1, G2, G3, G4, G9 G28, G30, G31, G32, G34, G40 are main pumps without spare. G23A, G24A, G25A are main pumps with spare. Other equipment, Lighting Panel LP4 and Air Handling Unit AHU5 will not cause the plant to shut down.

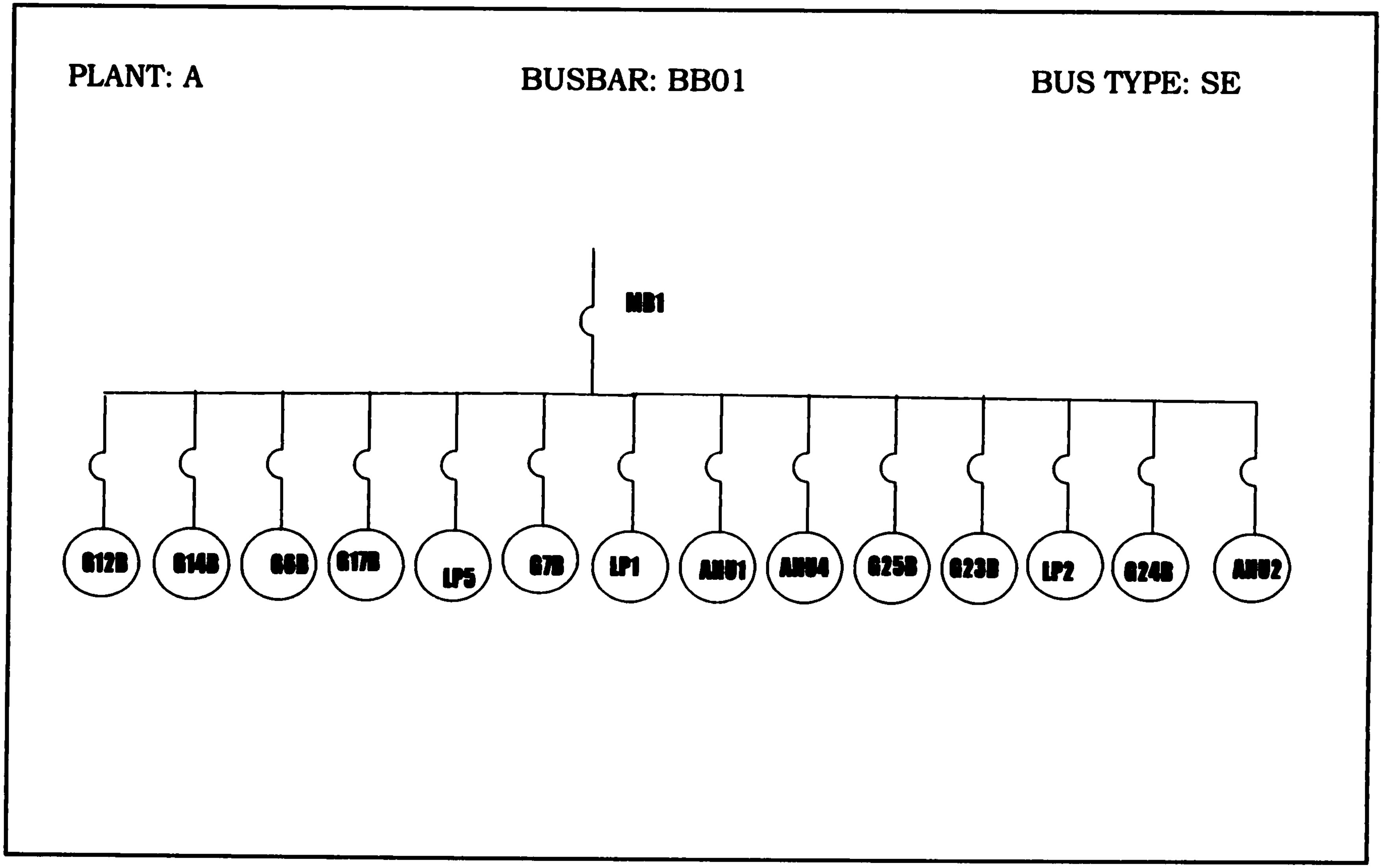


Figure 5.4: Single Line Diagram BB01 after arranging the load

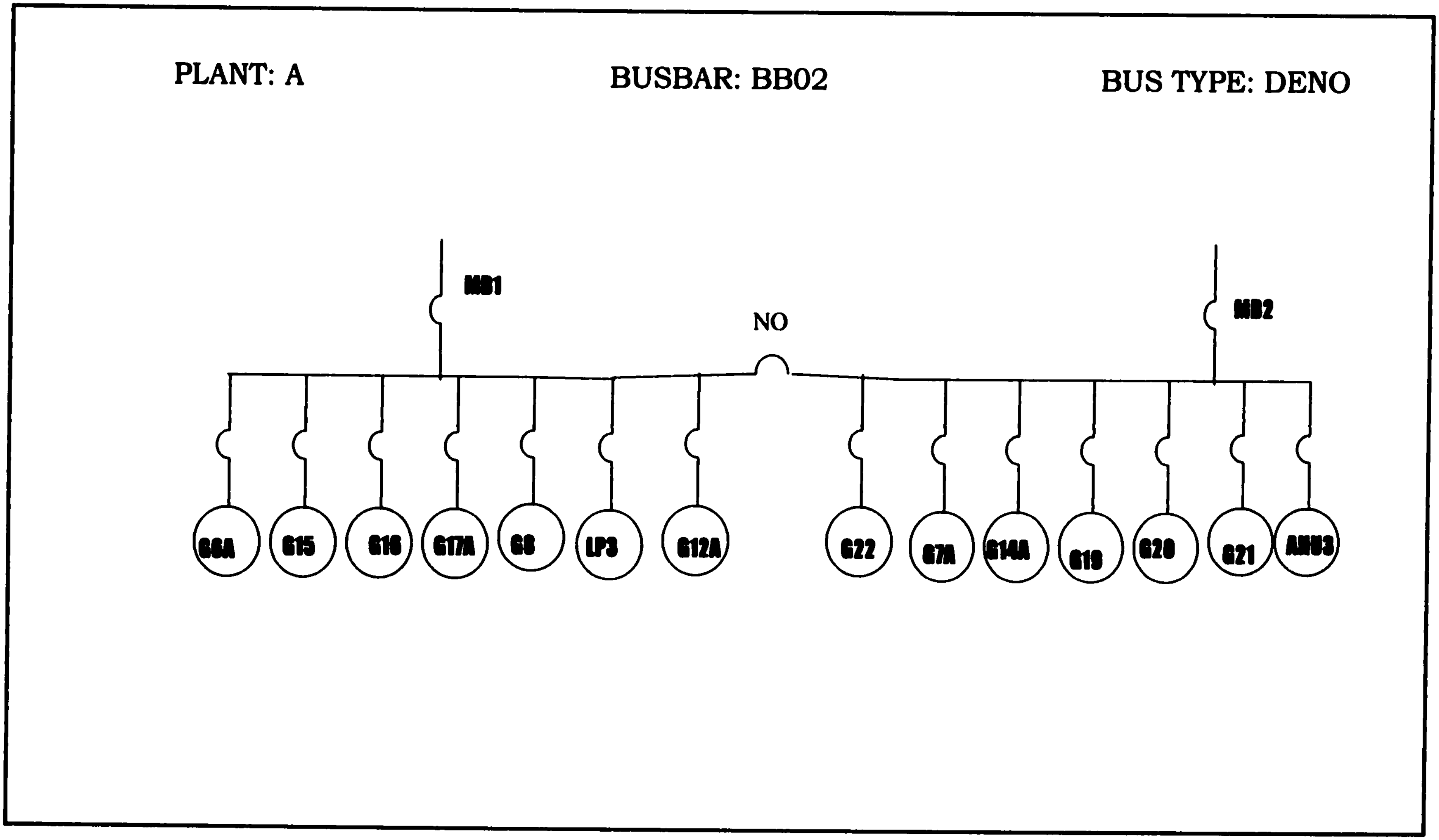


Figure 5.5: Single Line Diagram BB02 after arranging the loads

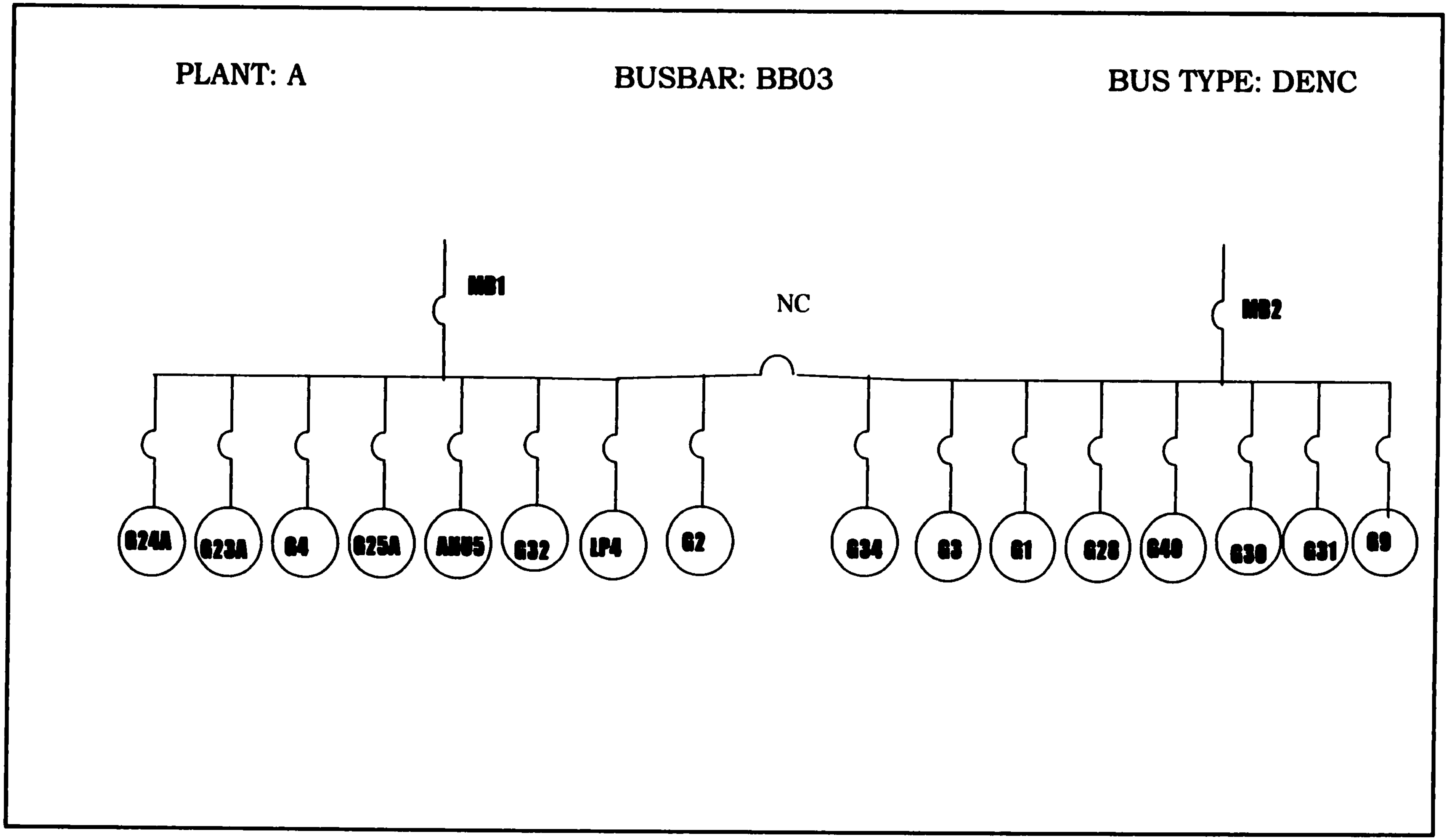


Figure 5.6: Single Line Diagram BB03 after arranging the load

The bus bar interruption table after re-arranging the loads for BB01 is not listed since there was no plant interruption. There was no effect in the plant since all the equipment connected in BB01 is either spare pumps or non critical loads even though the main breaker MB1 tripped.

Table 5.8 is the bus bar interruption table after arranging the plant loads for B002. It can be seen that the only critical equipment interrupted in B002 is G15 which led to one plant interruption. As it can be seen there is common interruption duration between MB1 and MB2 which led to plant interruption so, all the nine critical equipment connected the bus bar have been interrupted.

Table 5.9 is the bus bar interruption table after arranging the plant loads for B003. It can be seen that there are three critical equipments interrupted in B003 which are G1, G34, and G40 that led to one plant interruption. As it can be seen there is a common interruption duration between MB1 and MB2 which led to plant interruption so, all the nine critical equipment connected the bus bar have been interrupted.

Table 5-8: BBO2 Interruption Table after arranging the loads

No.	Equipment Interrupted	Number Of Bus bar Interruption	Number of equipment interruption	Bus bar Interruption Duration	Bus bar Interruption start Time	Bus bar Interruption Finishing Time
1	MB1_MB2	1	12	10.17	06/16/01 10:50 Hr	06/16/01 21:00 Hr
2	G15	1	1	2	06/18/01 11:00 Hr	06/18/01 13:30 Hr
TOTALS		2	13	12.17		

Table 5-9: BBO3 Interruption Table after arranging the loads

No.	Equipment Interrupted	Number Of Bus bar Interruption	Number of equipment interruption	Bus bar Interruption Duration	Bus bar Interruption start Time	Bus bar Interruption Finish Time
1	G40	1	1	0.67	01/01/01 12:20 Hr	01/01/01 13:00 Hr
2	G1	1	1	1	05/14/01 12:00 Hr	05/14/01 13:00 Hr
3	G34	1	1	0.17	06/18/01 20:50 Hr	06/18/01 21:00 Hr
4	MB1_MB2	1	14	1.5	09/09/01 12:30 Hr	09/09/01 14:00 Hr
TOTALS		4	17	3.34		

Table 5.10 is the plant interruption table before arranging the plant loads. The function of this table is to combine the common interruption durations between the plant bus bars. As it can be noticed there is no common duration between the bus bars.

Table 5-10: Plant Interruption Table after arranging the loads

No	Bus bars Interrupted	Number of Plant Interruptions	Plant Interruption Durations	Plant Interruption start Time	Plant Interruption Finish Time
1	BB03	1	0.67	1/1/2001 12:20:00 PM	1/1/2001 1:00:00 PM
2	BB03	1	1	5/14/2001 12:00:00 PM	5/14/2001 1:00:00 PM
3	BB02	1	10.17	6/16/2001 10:50:00 AM	6/16/2001 9:00:00 PM
4	BB02	1	2	6/18/2001 11:00:00 AM	6/18/2001 1:00:00 PM
5	BB03	1	0.17	6/18/2001 8:50:00 PM	6/18/2001 9:00:00 PM
6	BB03	1	1.5	9/9/2001 12:30:00 PM	9/9/2001 2:00:00 PM
TOTALS		6	15.51		

Table 5.11 summarizes the industrial plant reliability data before arranging the loads in order to us it in the industrial plant reliability indices calculation.

Table 5.12 shows the industrial plant reliability indices for plant A after arranging the load. These indices calculated by using the data mentioned in table 5.11 and the industrial plant reliability indices equations mentioned in chapter 4. The plant re-startup time is assumed to be 3 hours. The plant production cost per hour is assumed to be $500, 000 and the investment of the new equipment for that year is $2MM. The plant shut down cost after the modification is assumed to be $500,000. The maintenance cost before the modification is assumed to be $750,000 and after the modification to be$500,000.

Table 5-11: Reliability summary data after arranging the loads

Total Equipment Connected	Total Individual Equipment Interrupted	Total Equipment Interrupted	Total plant Interruptions	Total plant Interruptions Duration
26.00	26.00	30.00	6.00	15.51

Table 5-12: Industrial Plant Reliability indices after arranging the loads

PEAIFI	PIEAFI	PAIFI	PAIDI	APAI	PSC	PACSI
1.15	1.00	0.23	1.29	99.62	698,125.00	240,625.00

5.4 The effect of re-arranging the loads on the industrial plants reliability indices

The reliability improved significantly as shown in Table 5.7 and Table 5.12 when the load re-arranged utilizing the same equipment interruption data. For example, the PSCI after arranging the loads decreased from $1,250,208 to $698,125 and the PACSI decreased from $3,001,041 to $240,625.

From this it can be seen that the changes in the load arrangement led to a major difference in cost saving and plant shut down cost. By selecting the proper arrangement of the plant loads in the plant design stages and modifying the existing plants arrangement major plant shut down cost can be saved.

Chapter 6

PROPOSED INDUSTRIAL PLANTS RELIABILITY UPGRADING EVALUATION THROUGH CASE STUDIES

6.1 Introduction

Upgrading assumptions are shown in this chapter. The bus bars upgrading assumptions are used to upgrade the bus bar types. In order to show the changes in the industrial plants reliability indices when upgrading the substation bus bars, six upgrading cases were studied. Plant 'A' with three different bus bars and different equipment were studied in this chapter. A conclusion based on the PCASI is drawn out in this chapter in order to assist the plant management and engineers to decide the best upgrading option.

6.2 Upgrading Assumptions

In the bus bars upgrading from one type to another, the single equipment interruption will not be changed while the main breaker interruption will be changed. Upgrading the buses can be summarized as follows:

6.2.1 Upgrading Single Ended (SE) bus-bar to Double Ended Normally Open (DENO) bus bar

To upgrade SE bus-bar to DENO bus-bar the following cases need to be considered. In the SE bus-bar there is only one main as shown in Fig 6.1 However in the DENO bus bar there are two main circuit breakers and one tiebreaker as shown in Figure 6.2. So, there will be five failure options in the system,

A) Main breaker 1 and Main breaker 2 will trip at the same time and the load will be lost

B) Main breaker 1 will trip, tiebreaker will not close, and the load will be lost.

C) Main breaker 2 will trip, tiebreaker will not close, and the load will be lost.

D) Main breaker 1 will trip, main breaker 2 will not trip, and the load will not be lost.

E) Main breaker 2 will trip, main breaker 1 will not trip, and the load will not be lost.

In this case, the double-ended normally opened bus-bar is $^3/_5$ of the SE bus bar failure. So, in order to upgrade from SE bus bar to a DENO bus bar, the main breaker interruption is considered as 0.6 of the SE main breaker interruption.

6.2.2 Upgrading SE bus bar to Double Ended Normally Close (DENC) bus-bar

To upgrade the SE bus bar to a DENC bus-bar, the following cases need to be considered. In the SE bus-bar there is only one main breaker, if tripped the bus bar will be lost as shown in Figure 6.1. However in the DENC bus bar as shown in Figure 6.3, there are two breakers so, there will be three options

A) Main breaker 1 and Main breaker 2 will trip at the same time and the load will be lost

B) Main breaker 1 will trip, main breaker 2 will not trip, and the load will not be lost.

C) Main breaker 2 will trip, main breaker 1 will not trip, and the load will not be lost.

In this case, the DENC bus bar is $^1/_3$ of the SE bus bar so, if we upgrade from SE bus bar to a DENC bus bar, the main breaker interruption will be 0.3333 of the SE main breaker interruption.

6.2.3 Upgrading DENO tie breaker bus bar to DENC bus bar

In this case, the tiebreaker interruption in the DENO should not be considered, since the tie breaker in the DENO remains closed so, there is no chance of interruption due to the failure of closing the tie breaker.

6.3 Case Studies

To illustrate the upgrading options three bus systems were studied. The three buses are SE, DENO and DENC bus-bars as shown in Fig 6.1, 6.2 and 6.3 respectively.

The upgrading options of this substation are as follows;

A) Upgrade the BB01 SE bus to DENO bus,

B) Upgrade the BB01 SE bus to DENC bus,

C) Upgrade the BB02 DENO bus to DENC bus

D) Upgrade the BB02 DENO bus to DENC bus and the BB01 SE bus to DENO bus

E) Upgrade the BB02 DENO bus to DENC bus and the BB01 SE bus to DENC bus

Table 6.1 shows the plant interrupted equipment, the bus bar of the interrupted equipment and the equipment interruption duration starting and finishing time of the plant A. The interrupted equipment in all the three bus bars were listed in this table with their interruption duration in order to calculate the industrial plant reliability indices.

Table 6-1: Interruption Data for Plant A

No.	Bus bar number	Interrupted Equipment	Interruption start Time	Interruption Finish Time
1	BB01	AHU2	05/09/01 17:00 Hr	05/09/01 23:00 Hr
2	BB01	G1	05/14/01 12:00 Hr	05/14/01 13:00 Hr
3	BB01	G6	01/01/01 2:02 Hr	01/01/01 5:05 Hr
4	BB01	G7A	03/03/01 11:00 Hr	03/03/01 12:30 Hr
5	BB01	G7B	01/01/01 1:01 Hr	01/01/01 3:01 Hr
6	BB01	LP1	06/16/01 20:00 Hr	06/16/01 22:00 Hr
7	BB01	MB1	06/16/01 19:00 Hr	06/17/01 23:30 Hr
8	BB02	G14A	06/18/01 12:00 Hr	06/18/01 14:00 Hr
9	BB02	G15	06/18/01 11:00 Hr	06/18/01 13:00 Hr
10	BB02	MB1	01/01/01 1:01 Hr	01/01/01 5:50 Hr
11	BB02	MB1	06/16/01 4:00 Hr	06/16/01 21:00 Hr
12	BB02	MB2	06/16/01 10:50 Hr	06/16/01 23:00 Hr
13	BB02	TIE	01/01/01 01:01 Hr	01/01/01 3:00 Hr
14	BB03	G23A	08/02/01 11:00 Hr	08/02/01 13:00 Hr
15	BB03	G34	06/18/01 20:50 Hr	06/18/01 21:00 Hr
16	BB03	G40	01/01/01 12:20 Hr	01/01/01 13:00 Hr
17	BB03	MB1	09/09/01 12:30 Hr	09/09/01 15:00 Hr
18	BB03	MB2	09/09/01 12:00 Hr	09/09/01 14:00 Hr
19	BB03	MB2	09/02/01 1:02 Hr	09/02/01 3:02 Hr

6.3.1 Existing substation reliability indices calculation before upgrade

Figure 6.1 shows a single line diagram of a SE Bus-bar called BB01. A SE bus-bar is a bus-bar with one main breaker feeding the connected equipment to it. Fourteen different equipment listed in BB01 are fed from the single main breaker MB1. Among those equipment G1, G2, G3, G4, G6, G8, G9, G70 are main pumps without spare. If any from these pumps trips, the plant will be shut down. G7A and G7B are main pumps with spare. If any from these pumps trips the spare pump will take over. The plant will be shut down only both pumps are tripped at the same time. Other equipment, Lighting Panel LP1, LP2 and Air Handling Unit AHU1and AHU2 will not cause the plant to shut down.

Figure 6.2 shows a single line diagram of a DENO tie breaker Bus-bar called BB02. A DENO tie breaker bus-bar is a bus-bar with two main breakers feeding the equipment connected to the bus-bar along with normally opened tie breaker that will close when one of the main breakers is tripped. Fourteen different equipment listed in BB02 are fed from the two main breakers MB1 and MB2. Among those equipment G15, G16, G19, G20, G21, G22 are main pumps without spare. If any of these pumps trips, the plant will be shut down. G12A, G12B, G14A, G14B, G17A and G17B are main pumps with spare. If any from these pumps trips the spare pump will take over. The plant will be shut down only both pumps are tripped at the same time. Other equipment, Lighting Panel LP3 and Air Handling Unit AHU3 will not cause the plant to shut down.

Figure 6.3 shows a single line diagram of a DENC tie breaker Bus-bar called BB03. A DENC tie-breaker bus bar is a bus-bar with two main breakers feeding the equipment connected to the bus-bar along with normally closed tie breaker. Sixteen different equipment listed in BB03 are fed from the two main breakers MB1and MB2. Among those equipment G28, G30, G31, G32, G34, G40 are main pumps without spare. G23A, G23B, G24A, G24B, G25A and G25B are main pumps with spare. Other equipment, Lighting Panel LP4, LP5 and Air Handling Unit AHU4, AHU5 will not cause the plant to shut down

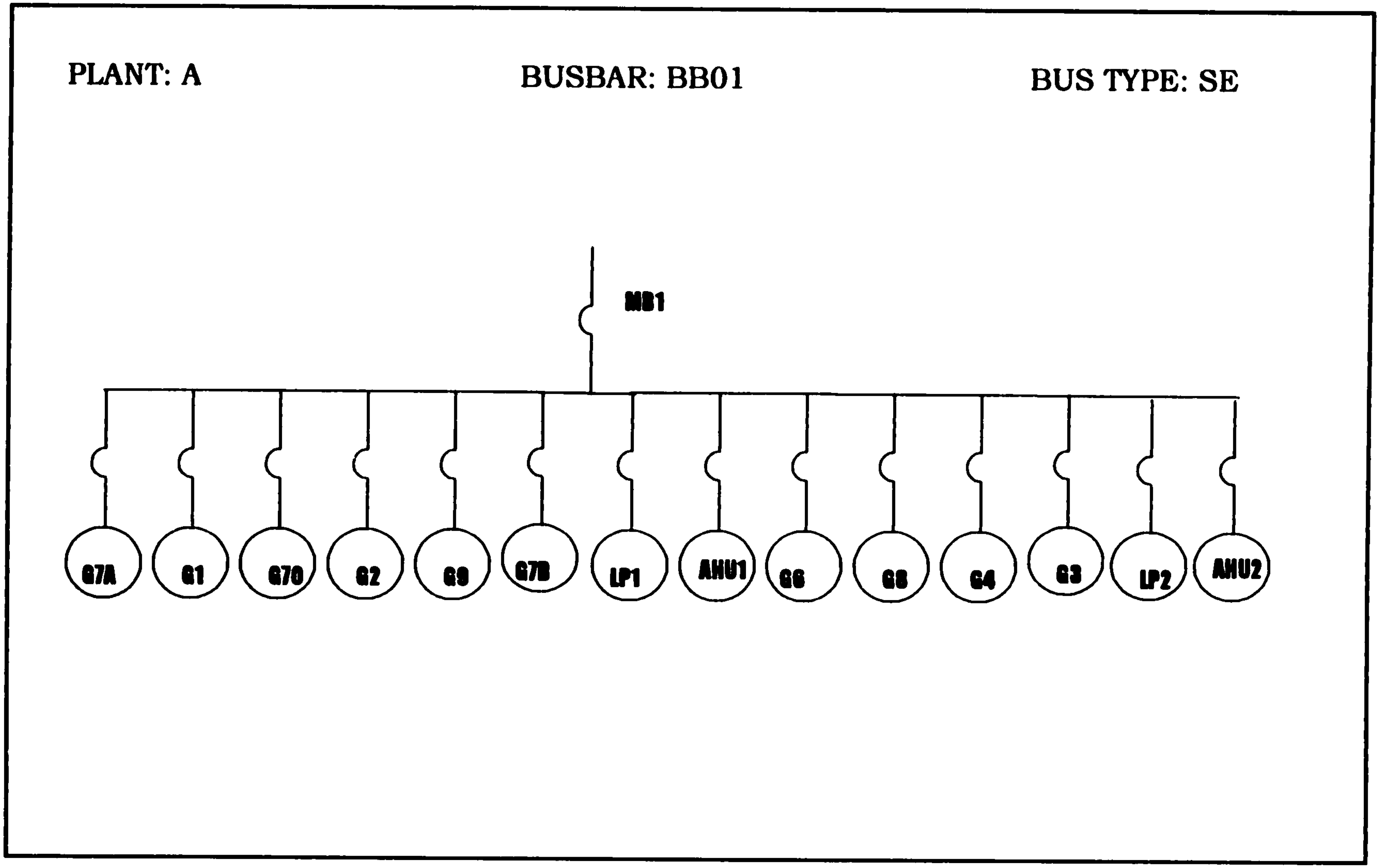


Figure 6.1: Single Line Diagram BB01 before upgrading the bus-bar

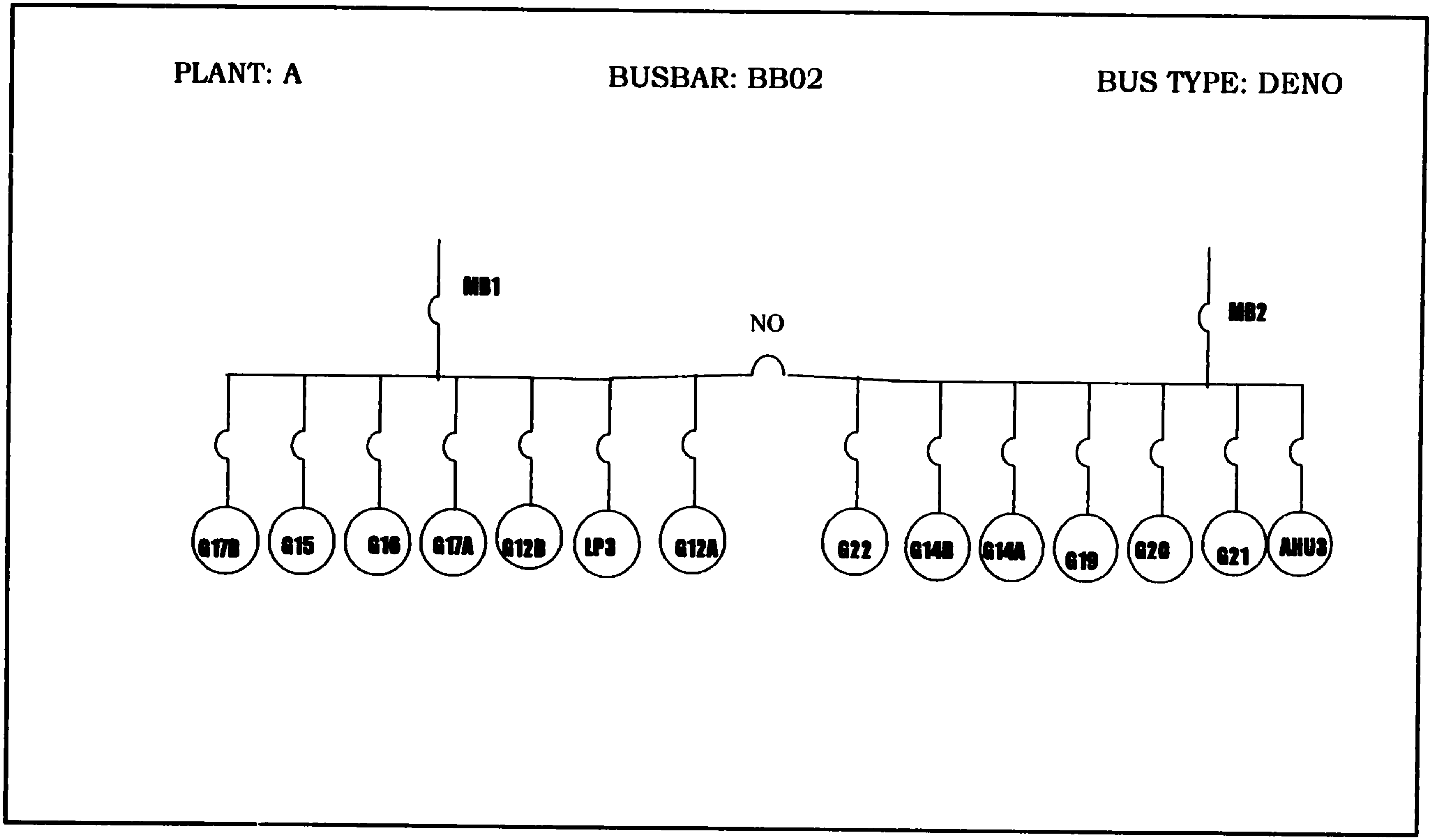


Figure 6.2: Single Line Diagram BB02 before upgrading the bus-bar

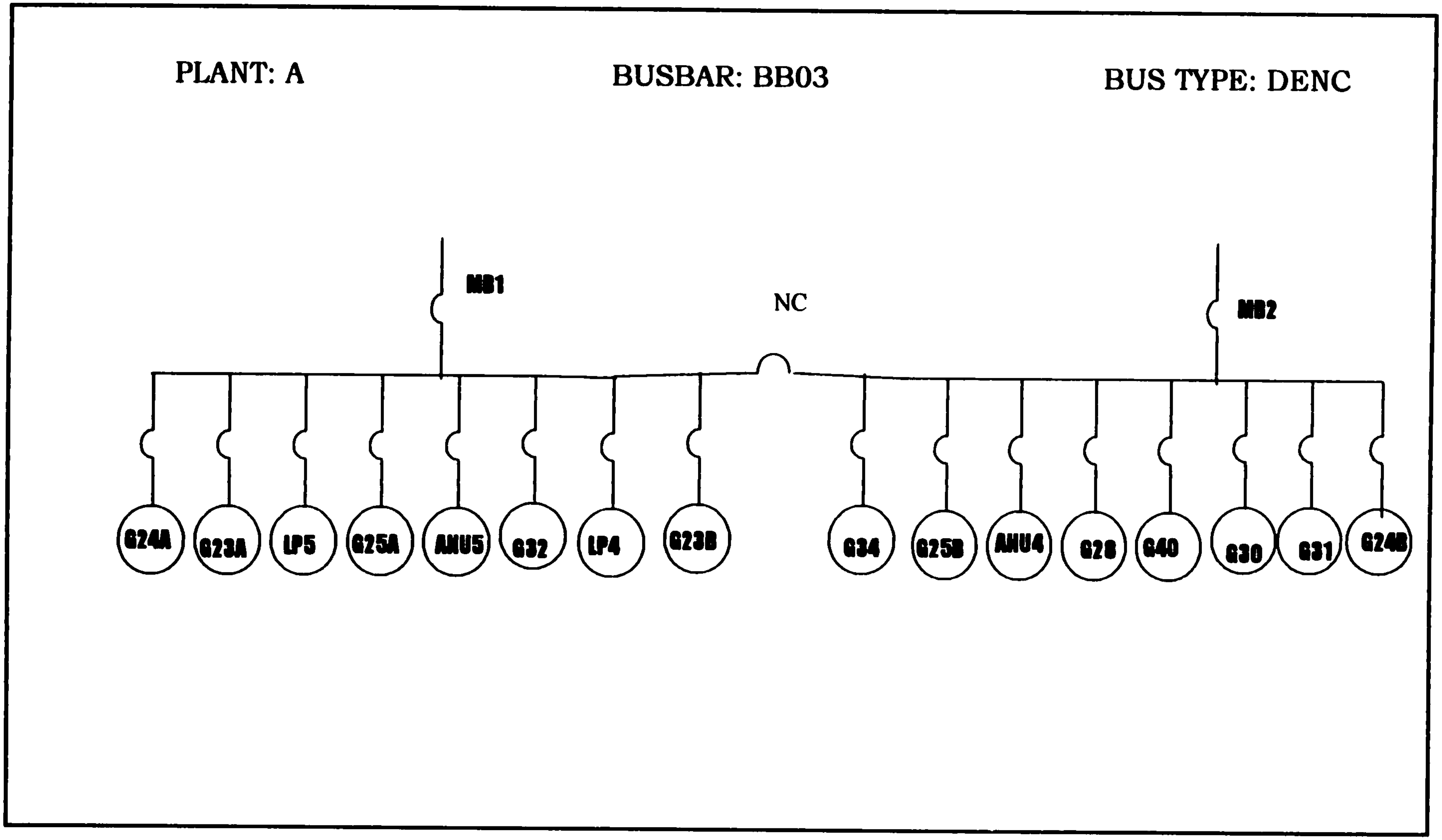


Figure 6.3: Single Line Diagram BB03 before upgrading the bus-bar

Table 6.2 is the bus bar interruption table for the an existing substation before any upgrade for B001 which shows the critically interrupted equipment, the number of equipment interruption, bus bar interruption duration, the bus bar interruption start and finish time. The bus bar interruption duration is the difference between the bus bar interruption start and finish time in hours. It can be seen that there are two critical equipment interrupted in B001; G1 and G6, which led to one plant interruption. The main breaker is also considered critical, which led to another plant interruption and since B001 is SE bus bar, all the nine critical equipment connected to the bus bar have been interrupted.

Table 6.3 is the bus bar interruption table for the existing substation before any upgrade for B002. It can be seen that the only critical equipment interrupted in B002 is G15 which led to one plant interruption. As it can be seen there is common interruption duration between MB1 and MB2, MB1 and tie-breaker (TIE) which led to plant interruption so, all the nine critical equipment connected to the bus bar had been interrupted.

Table 6-2: BBO1 Interruption Table before upgradation

No.	Equipment Interrupted	Number Of Bus bar Interruption	Number of equipment interruption	Bus bar Interruption Duration	Bus-bar Interruption starting time	Bus-bar Interruption finishing time
1	G6	1	1	3.05	01/01/01 2:02 Hr	01/01/01 5:05 Hr
2	G1	1	1	1	05/14/01 12:00 Hr	05/14/01 13:00 Hr
3	MB1	1	9	28.5	06/16/01 19:00 Hr	06/17/01 23:30 Hr
TOTALS		3	11	32.55		

Table 6-3: BBO2 Interruption Table before upgradation

No.	Equipment Interrupted	Number Of Bus bar Interruption	Number of equipment interruption	Bus bar Interruption Duration	Bus bar Interruption starting time	Bus bar Interruption finishing time
1	TIE_MB1	1	4	1.98	01/01/01 1:01 Hr	01/01/01 3:00 Hr
2	MB1_MB2	1	9	10.17	06/16/01 10:50 Hr	06/16/01 21:00 Hr
3	G15	1	1	2	06/18/01 11:00 Hr	06/18/01 13:00 Hr
TOTALS		3	14	14.15		

Table 6.4 is the bus bar interruption table for the existing substation before any upgrade for B003. It can be seen that there are two critical equipment interrupted in B003 which are G34, G40 that led to one plant interruption. As it can be seen there is common interruption duration between MB1 and MB2 which led to plant interruption so, all the nine critical equipment connected the bus bar been interrupted.

Table 6.5 is the plant interruption table for an existing substation before any upgrade, which shows the interrupted bus bar, the number of plant interruptions, plant interruption duration, the plant interruption starting and finishing time. The function of this table is to combine the common interruption durations between the plant bus bars. As it can be noticed that there are two common interruption durations between B002 and B001, which is considered as two plant interruption even though each bus bar was interrupted twice.

Table 6-4: BBO2 Interruption Table before upgradation

No.	Equipment Interrupted	Number Of Bus bar Interruption	Number of equipment interruption	Bus bar Interruption Duration	Bus bar Interruption starting time	Bus bar Interruption Finishing Time
1	G40	1	1	0.67	01/01/01 12:20 Hr	01/01/01 13:00 Hr
2	G34	1	1	0.17	06/18/01 20:50 Hr	06/18/01 21:00 Hr
3	MB1_ MB2	1	9	1.5	09/09/01 12:30 Hr	09/09/01 14:00 Hr
TOTALS		3	11	2.34		

Table 6-5: Plant Interruption Table before upgradation

No	Bus bars Interrupted	Number Of Plant Interruptions	Plant Interruption Durations	Plant Interruption starting Time	Plant Interruption Finishing Time
1	BB02, BB01	1	4.07	1/1/2001 1:01:00 AM	1/1/2001 5:05:00 AM
2	BB03	1	0.67	1/1/2001 12:20:00 PM	1/1/2001 1:00:00 PM
3	BB01	1	1	5/14/2001 12:00:00 PM	5/14/2001 1:00:00 PM
4	BB02, BB01	1	36.67	6/16/2001 10:50:00 AM	6/17/2001 11:30:00 PM
5	BB02	1	2	6/18/2001 11:00:00 AM	6/18/2001 1:00:00 PM
6	BB03	1	0.17	6/18/2001 8:50:00 PM	6/18/2001 9:00:00 PM
7	BB03	1	1.5	9/9/2001 12:30:00 PM	9/9/2001 2:00:00 PM
TOTALS		7	46.08		

Table 6.6 summarizes the industrial plant reliability data for the existing substation before any upgrade in order to be used in the industrial plant reliability indices calculation. Table 6.5 shows the total equipment connected in the plant, total individual equipment interrupted in the plant, total equipment interrupted in the plant, total plant interruptions and total plant interruption duration.

Table 6.7 shows the industrial plant reliability indices for plant A for an existing substation before any upgrade. These indices calculated by using the data mentioned in table 6.6 and the industrial plant reliability indices equations mentioned in chapter 4. The plant re-startup time assumed to be 3 hours. The plant production cost per hour is assumed to be $500,000.

Table 6-6: Plant summary data before upgradation

Total Equipment Connected	Total Individual Equipment Interrupted	Total Equipment Interrupted	Total plant Interruptions	Total plant Interruptions Duration
27.00	27.00	36.00	7.00	46.08

Table 6-7: Industrial Plant Reliability Indices before Upgradation.

PEAIFI	PIEAFI	PAIFI	PAIDI	APAI	PSC
1.33	1.00	0.259	2.48	99.23	1,397,500.00

6.3.2 Case A: Upgrading the SE bus bar BB01 to DENO bus bar

Figure 6.4 shows single line diagram of B001 upgraded to DENO Bus-bar. The same fourteen different equipment listed in BB01 but are fed from two main breakers MB1 & MB2 along with normally open tie breaker that will close when one of the main breakers is tripped.

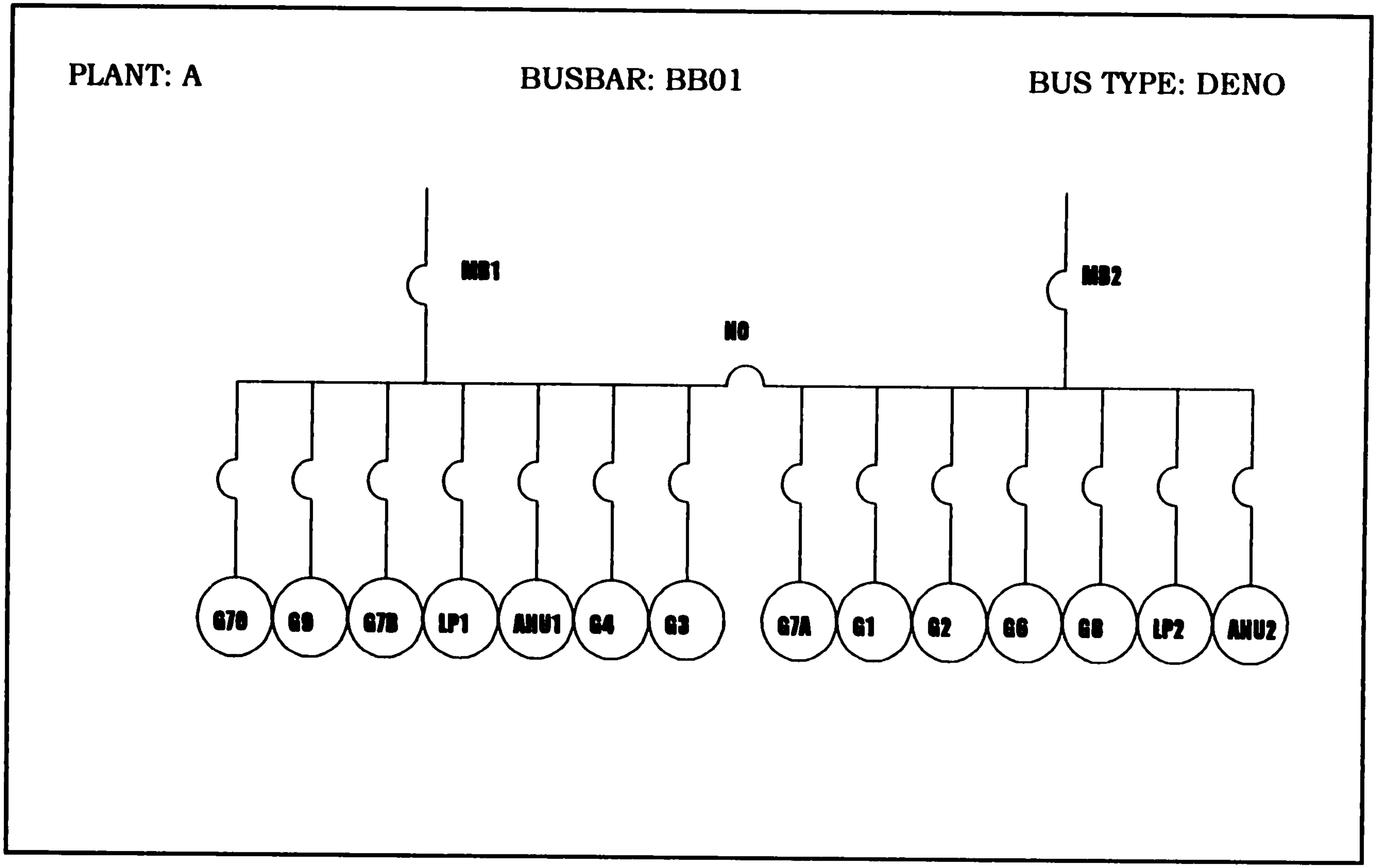


Figure 6.4: Single Line Diagram BB01 after upgrading the SE to DENO

Table 6.8 is the bus bar interruption table after upgrading the SE bus bar BB01 to DENO bus bar. The changes in the bus bar interruption duration based on the upgrading assumptions can be noticed between Table 6.2 and this table.

In this case the only bus bar upgraded from SE bus bar to DENO, BB01. Table 6.3 and Table 6.4 will remain unchanged for the DENO bus bar BB02 and the DENC bus bar BB03. Table 6.9 shows the plant interruption table after upgrading the SE bus bar BB01 to DENO bus bar

Table 6-8: Case A: BBO1 Interruption Table

No.	Equipment Interrupted	Number Of Bus bar Interruption	Number of equipment interruption	Bus bar Interruption Duration	Bus-Bar Interruption starting Time	Bus bar Interruption Finishing Time
1	G6	1	1	3.05	01/01/01 2:02 Hr	01/01/01 5:05 Hr
2	G1	1	1	1	05/14/01 12:00 Hr	05/14/01 13:00 Hr
3	MB1_MB2	1	9	17.1	06/16/01 19:00 Hr	06/17/01 12:06 Hr
TOTALS		3	11	21.15		

Table 6-9: Case A: Plant Interruption Table

No	Bus bars Interrupted	Number of Plant Interruptions	Plant Interruption Durations	Plant Interruption Starting Time	Plant Interruption Finishing Time
1	BB02, BB01	1	4.07	1/1/2001 1:01:00 AM	1/1/2001 5:05:00 AM
2	BB03	1	0.67	1/1/2001 12:20:00 PM	1/1/2001 1:00:00 PM
3	BB01	1	1	5/14/2001 12:00:00 PM	5/14/2001 1:00:00 PM
4	BB02, BB01	1	25.27	6/16/2001 10:50:00 AM	6/17/2001 12:06:00 PM
5	BB02	1	2	6/18/2001 11:00:00 AM	6/18/2001 1:00:00 PM
6	BB03	1	0.17	6/18/2001 8:50:00 PM	6/18/2001 9:00:00 PM
7	BB03	1	1.5	9/9/2001 12:30:00 PM	9/9/2001 2:00:00 PM
TOTALS		7	34.68		

Table 6.10 summarizes the industrial plant reliability data when upgrading the SE bus bar BB01 to DENO bus bar in order to us it in the industrial plant reliability indices calculation.

Table 6.11 shows the industrial plant reliability indices for plant A when upgrading the SE bus bar BB01 to DENO bus bar. These indices calculated by using the data mentioned in table 6.10 and the industrial plant reliability indices equations mentioned in chapter 4.

Table 6-10: Case A: Plant summary data

Total Equipment Connected	Total Individual Equipment Interrupted	Total Equipment Interrupted	Total plant Interruptions	Total plant Interruptions Duration
28.00	28.00	37.00	7.00	34.68

Table 6-11: Case A: Industrial Plant Reliability Indices.

PEAIFI	PIEAFI	PAIFI	PAIDI	APAI	PSC
1.32	1.00	0.25	1.99	99.36	1,160,000.00

As it can be seen the PAIDI, PAAI and the PSCI is improved when the substation bus bar upgraded. The saving between the existing substation configuration and this upgrade will be calculated in section 6.4.

6.3.3 Case B: Upgrading the SE bus bar BB01 to DENC bus bar

Figure 6.5 shows single line diagram of B001 upgraded to DENC Bus-bar. The same fourteen different equipment listed in BB01 but are fed from two main breakers MB1 & MB2 along with normally closed tie breaker.

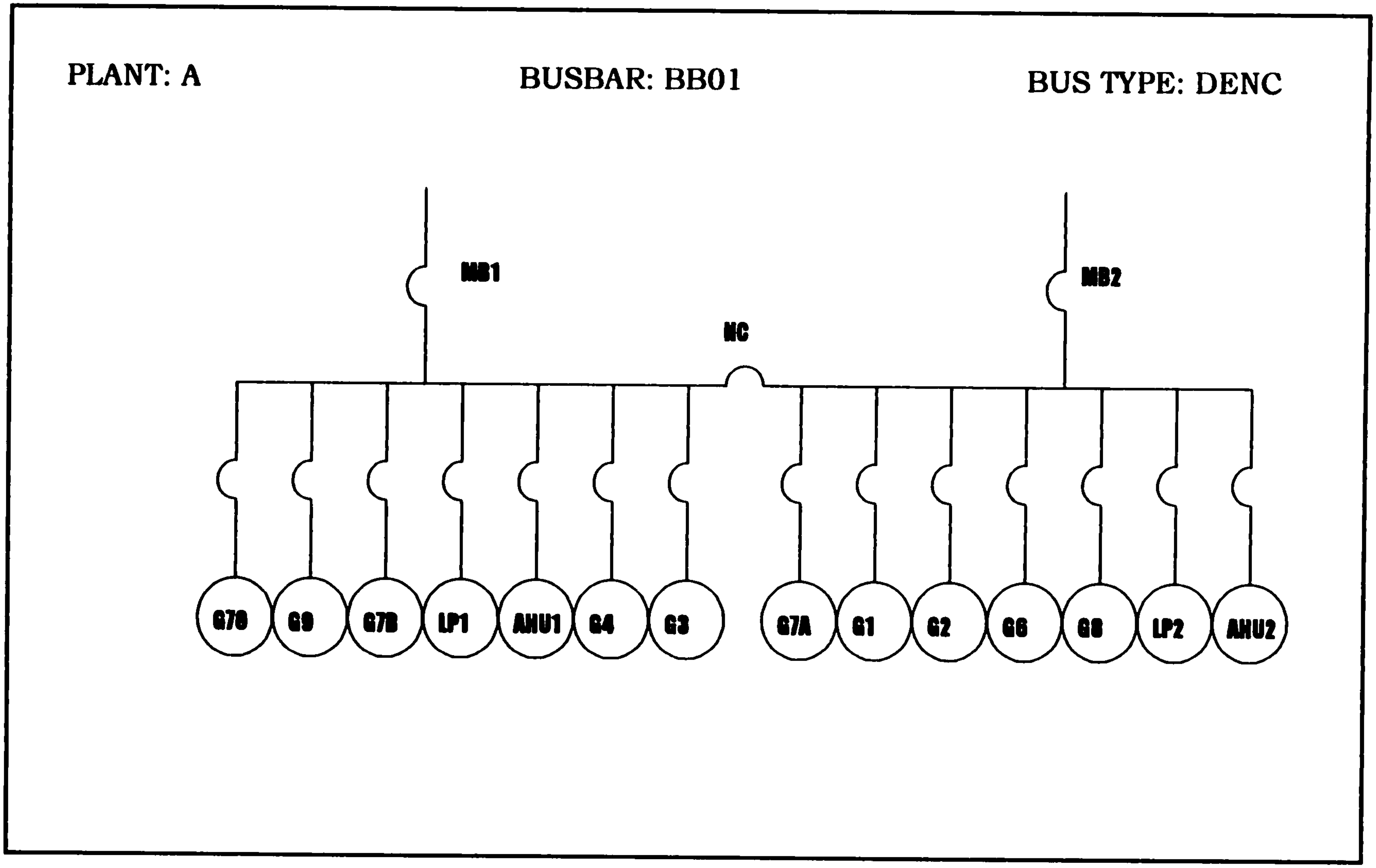


Figure 6.5: Single Line Diagram BB01 after upgrading the SE to DENC

Table 6.12 is the bus bar interruption table after upgrading the SE bus bar BB01 to DENC bus bar. The changes in the bus bar interruption duration based on the upgrading assumptions can be noticed between Table 6.2 and this table.

In this case the only bus bar upgraded from SE to DENC bus bar is BB01. Table 6.3 and Table 6.4 will remain unchanged for the DENO bus bar BB02 and the DENC bus bar BB03. Table 6.13 shows the plant interruption table after upgrading the SE bus bar BB01 to DENC bus bar.

Table 6-12: Case B: BBO1 Interruption Table

No.	Equipment Interrupted	Number Of Bus bar Interruption	Number of equipment interruption	Bus bar Interruption Duration	Bus bar Interruption Starting time	Bus bar Interruption Finishing Time
1	G6	1	1	3.05	01/01/01 2:02 Hr.	01/01/01 5:05 Hr
2	G1	1	1	1	05/14/01 12:00 Hr	05/14/01 13:00 Hr
3	MB1_MB2	1	9	9.5	06/16/01 19:00 Hr	06/17/01 4:30 Hr
TOTALS		3	11	13.55		

Table 6-13: Case B: Plant Interruption Table

No	Bus bars Interrupted	Number Of Plant Interruptions	Plant Interruption Durations	Plant Interruption starting Time	Plant Interruption Finishing Time
1	BB02, BB01	1	4.07	1/1/2001 1:01:00 AM	1/1/2001 5:05:00 AM
2	BB03	1	0.67	1/1/2001 12:20:00 PM	1/1/2001 1:00:00 PM
3	BB01	1	1	5/14/2001 12:00:00 PM	5/14/2001 1:00:00 PM
4	BB02, BB01	1	17.67	6/16/2001 10:50:00 AM	6/17/2001 4:30:00 AM
5	BB02	1	2	6/18/2001 11:00:00 AM	6/18/2001 1:00:00 PM
6	BB03	1	0.17	6/18/2001 8:50:00 PM	6/18/2001 9:00:00 PM
7	BB03	1	1.5	9/9/2001 12:30:00 PM	9/9/2001 2:00:00 PM
TOTALS		7	27.08		

Table 6.14 summarizes the industrial plant reliability data when upgrading the SE bus bar BB01 to DENC bus bar in order to us it in the industrial plant reliability indices calculation.

Table 6.15 shows the industrial plant reliability indices for plant A when upgrading the SE bus bar BB01 to DENC bus bar. These indices calculated by using the data mentioned in table 6.14 and the industrial plant reliability indices equations mentioned in chapter 4.

Table 6-14: Case B: Plant summary data

Total Equipment Connected	Total Individual Equipment Interrupted	Total Equipment Interrupted	Total plant Interruptions	Total Plant Interruptions Duration
28.00	28.00	37.00	7.00	27.08

Table 6-15: Case B: Industrial Plant Reliability Indices.

PEAIFI	PIEAFI	PAIFI	PAIDI	APAI	PSC
1.32	1.00	0.25	1.72	99.45	1,001,666.67

As it can be seen the PAIDI, PAAI and the PSCI is improved when the substation bus bar upgraded. The saving between the existing substation configuration and this upgrade will be calculated in section 6.4.

6.3.4 Case C: Upgrading the DENO bus bar BB02 to DENC bus bar

Figure 6.6 shows single line diagram of B002 upgraded to DENC Bus-bar. The same fourteen different equipment listed in BB02 but are fed from two main breakers MB1 & MB2 along with normally closed tie breaker.

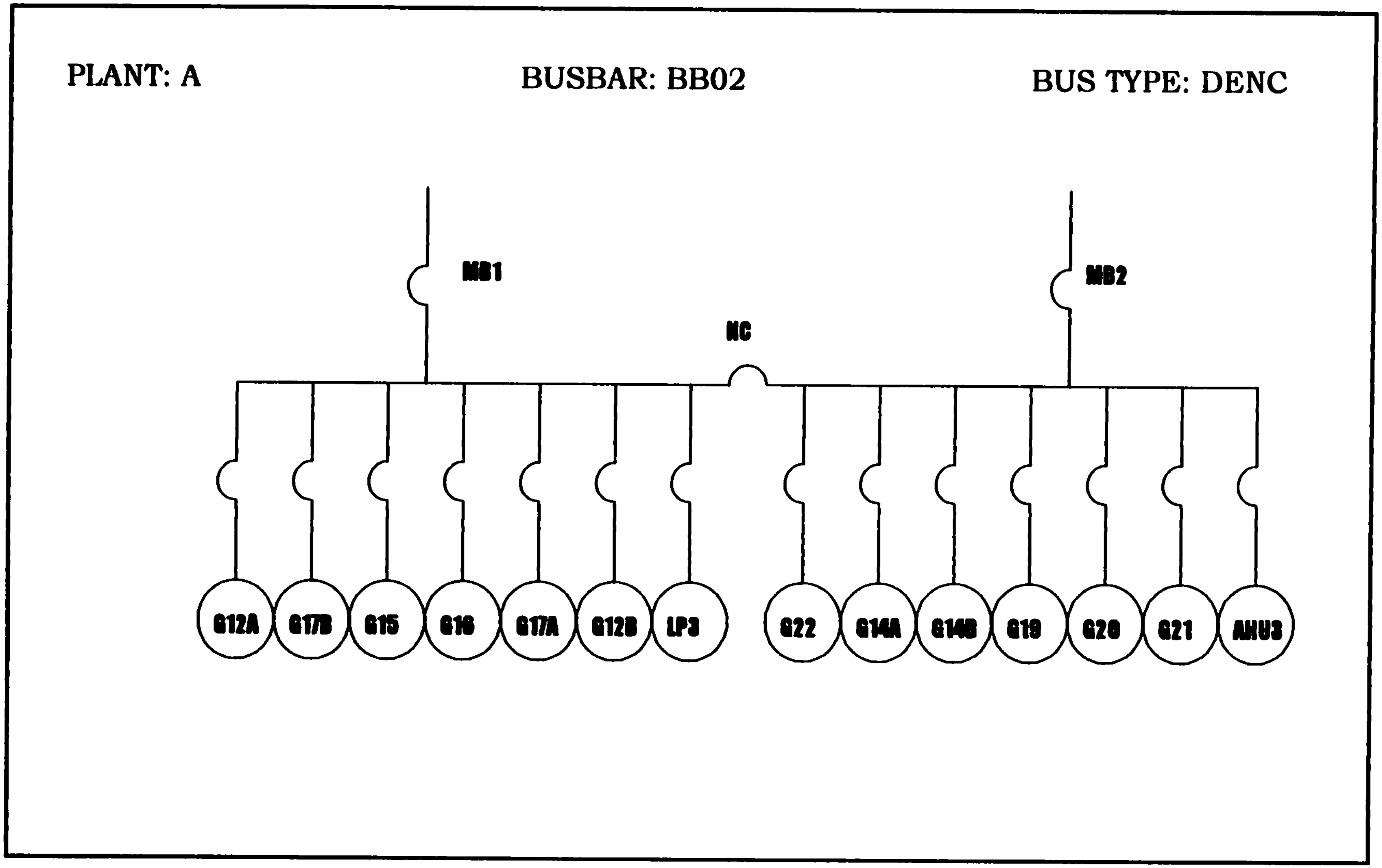


Figure 6.6: Single Line Diagram BB02 after upgrading the DENO to DENC

Table 6.16 is the bus bar interruption table after upgrading the DENO bus bar BB02 to DENC bus bar. The changes in the bus bar interruption duration based on the upgrading assumptions can be noticed between Table 6.3 and this table.

In this case the only bus bar upgraded from DENO to DENC bus bar is BB02. Table 6.2 and Table 6.4 will remain unchanged for the SE bus bar BB01 and the DENC bus bar BB03. Table 6.17 shows the plant interruption table after upgrading the DENO bus bar BB02 to DENO bus bar.

Table 6-16: Case C: BBO2 Interruption Table

No.	Equipment Interrupted	Number Of Bus bar Interruption	Number of equipment interruption	Bus bar Interruption Duration	Bus bar Interruption starting Time	Bus bar Interruption Finishing Time
1	MB1_MB2	1	9	10.17	06/16/01 10:50 Hr.	06/16/01 21:00 Hr
2	G15	1	1	2	06/18/01 11:00 Hr	06/18/01 13:00 Hr
TOTALS		2	10	12.17		

Table 6-17: Case C: Plant Interruption Table

No	Bus bars Interrupted	Number of Plant Interruptions	Plant Interruption Durations	Plant Interruption starting Time	Plant Interruption Finishing Time
1	BB01	1	3.05	1/1/2001 2:02:00 AM	1/1/2001 5:05:00 AM
2	BB03	1	0.67	1/1/2001 12:20:00 PM	1/1/2001 1:00:00 PM
3	BB01	1	1	5/14/2001 12:00:00 PM	5/14/2001 1:00:00 PM
4	BB02, BB01	1	36.67	6/16/2001 10:50:00 AM	6/17/2001 11:30:00 PM
5	BB02	1	2	6/18/2001 11:00:00 AM	6/18/2001 1:00:00 PM
6	BB03	1	0.17	6/18/2001 8:50:00 PM	6/18/2001 9:00:00 PM
7	BB03	1	1.5	9/9/2001 12:30:00 PM	9/9/2001 2:00:00 PM
TOTALS		7	45.06		

Table 6.18 summarizes the industrial plant reliability data when upgrading the DENO bus bar BB02 to DENC bus bar in order to us it in the industrial plant reliability indices calculation.

Table 6.19 shows the industrial plant reliability indices for plant A after upgrading the DENO bus bar BB02 to DENC bus bar. These indices calculated by using the data mentioned in table 6.18 and the industrial plant reliability indices equations mentioned in chapter 4.

Table 6-18: Case C: Plant summary data

Total Equipment Connected	Total Individual Equipment Interrupted	Total Equipment Interrupted	Total plant Interruptions	Total plant Interruptions Duration
28.00	28.00	33.00	7.00	45.06

Table 6-19: Case C: Industrial Plant Reliability Indices.

PEAIFI	PIEAFI	PAIFI	PAIDI	APAI	PSC
1.18	1.00	0.25	2.36	99.25	1,376,250.00

As it can be seen the PAIDI, PAAI and the PSCI is improved when the substation bus bar upgraded. The saving between the existing substation configuration and this upgrade will be calculated in section 6.4.

6.3.5 Case D: Upgrading the SE bus bar BB01 to DENO bus bar and DENO bus bar BB02 to DENC bus bar

The bus bar interruption Table 6.8 will be used for BB01and the bus bar interruption Table 6.16 will be used for BB02. Table 6.4 will remain unchanged. Table 6.20 shows the plant interruption table after upgrading the SE bus bar BB01 to DENO bus bar and DENO bus bar BB02 to DENC bus bar.

Table 6-20: Case D: Plant Interruption Table

No	Bus bars Interrupted	Number of Plant Interruptions	Plant Interruption Durations	Plant Interruption starting Time	Plant Interruption Finishing Time
1	BB01	1	3.05	1/1/2001 2:02:00 AM	1/1/2001 5:05:00 AM
2	BB03	1	0.67	1/1/2001 12:20:00 PM	1/1/2001 1:00:00 PM
3	BB01	1	1	5/14/2001 12:00:00 PM	5/14/2001 1:00:00 PM
4	BB02, BB01	1	25.27	6/16/2001 10:50:00 AM	6/17/2001 12:06:00 PM
5	BB02	1	2	6/18/2001 11:00:00 AM	6/18/2001 1:00:00 PM
6	BB03	1	0.17	6/18/2001 8:50:00 PM	6/18/2001 9:00:00 PM
7	BB03	1	1.5	9/9/2001 12:30:00 PM	9/9/2001 2:00:00 PM
TOTALS		7	33.66		

Table 6.21 summarizes the industrial plant reliability data when upgrading the SE bus bar BB01 to DENO bus bar and the DENO bus bar BB02 to DENC bus bar in order to us it in the industrial plant reliability indices calculation.

Table 6.22 shows the industrial plant reliability indices for plant A after upgrading the SE bus bar BB01 to DENO bus bar and the DENO bus bar BB02 to DENC bus bar. These indices calculated by using the data mentioned in table 6.21 and the industrial plant reliability indices equations mentioned in chapter 4.

Table 6-21: Case D: Plant summary data

Total Equipment Connected	Total Individual Equipment Interrupted	Total Equipment Interrupted	Total plant Interruptions	Total plant Interruptions Duration
28.00	28.00	33.00	7.00	33.66

Table 6-22: Case D: Industrial Plant Reliability Indices.

PEAIFI	PIEAFI	PAIFI	PAIDI	APAI	PSC
1.18	1.00	0.25	1.95	99.38	1,138,750.00

As it can be seen the PAIDI, PAAI and the PSCI is improved when the substation bus bar upgraded. The saving between the existing substation configuration and this upgrade will be calculated in section 6.4.

6.3.6 Case E: Upgrading the DENO bus to DENC bus and the SE bus to DENC bus

The bus bar interruption Table 6.12 will be used for BB01and the bus bar interruption Table 6.16 will be used for BB02. Table 6.4 will remain unchanged. Table 6.23 shows the plant interruption table after upgrading the SE bus bar BB01 to DENC bus bar and DENO bus bar BB02 to DENC bus bar.

Table 6-23: Case E : Plant Interruption Table

No	Bus bars Interrupted	Number of Plant Interruptions	Plant Interruption Durations	Plant Interruption starting Time	Plant Interruption Finishing Time
1	BB01	1	3.05	1/1/2001 2:02:00 AM	1/1/2001 5:05:00 AM
2	BB03	1	0.67	1/1/2001 12:20:00 PM	1/1/2001 1:00:00 PM
3	BB01	1	1	5/14/2001 12:00:00 PM	5/14/2001 1:00:00 PM
4	BB02, BB01	1	17.67	6/16/2001 10:50:00 AM	6/17/2001 4:30:00 AM
5	BB02	1	2	6/18/2001 11:00:00 AM	6/18/2001 1:00:00 PM
6	BB03	1	0.17	6/18/2001 8:50:00 PM	6/18/2001 9:00:00 PM
7	BB03	1	1.5	9/9/2001 12:30:00 PM	9/9/2001 2:00:00 PM
TOTALS		7	26.06		

Table 6.24 summarizes the industrial plant reliability data when upgrading the SE bus bar BB01 to DENC bus bar and the DENO bus bar BB02 to DENC bus bar in order to us it in the industrial plant reliability indices calculation.

Table 6.25 shows the industrial plant reliability indices for plant A after upgrading the SE bus bar BB01 to DENC bus bar and the DENO bus bar BB02 to DENC bus bar. These indices calculated by using the data mentioned in table 6.24 and the industrial plant reliability indices equations mentioned in chapter 4.

Table 6-24: Case E: Plant summary data

Total Equipment Connected	Total Individual Equipment Interrupted	Total Equipment Interrupted	Total plant Interruptions	Total plant Interruptions Duration
28.00	28.00	33.00	7.00	26.06

Table 6-25: Case E: Industrial Plant Reliability Indices.

PEAIFI	PIEAFI	PAIFI	PAIDI	APAI	PSC
1.18	1.00	0.25	1.68	99.46	980,416.67

As it can be seen the PAIDI, PAAI and the PSCI is improved when the substation bus bar is upgraded. The saving between the existing substation configuration and this upgrade will be calculated in section 6.4.

6.4 Upgrading decisions

Table 6.26 calculates the PACSI for the six case studies. The maintenance cost before and after the modification assumed to be the same $100,000. The investment of equipment in upgrading the SE bus bar to DENO bus bar for one year is assumed to be $50,000. The investment of equipment in upgrading the DENO bus bar to DENC bus bar for one year is assumed to be $25,000.

The higher investment of equipment for one year does not necessarily mean the best upgrading option and also the lower investment of equipment for one year does not also mean the worst upgrading option. In case E the investment of equipment for one year is $100,000 with PACSI of $317,083 compared to the investment cost in case B for one year which is $75,000 with PACSI of $320,834. In case D the investment of equipment for one year is

$75,000 with PACSI of $183,750 compared to the investment cost in case B for one year which is $50,000 with PACSI of $187,500.

The higher PSCI does not mean the worst PACSI after the plant upgrade and also the lower PSCI does not also mean the best PACSI. In case E the PSCI is $980,417 with PACSI of $317,083 compared to case B PSCI which is $101,666 with PACSI of $320,834. In case A the PSCI is $1,160,000 with PACSI of $187,500 compared to case B PSCI which is $101,666 with PACSI of $320,834.

Non all the upgrades ends with saving an example of that is Case "C" which led to loss of $-3,759. The best upgrading option was found to be case "B" which led to a cost saving of 320,834 yearly. Based on the cost saving index, the plant management can analyze and decide the best option to select for their plant upgrade.

Table 6-26: Plant Upgrading Evaluation Summary Table

Upgrading Case	Description	PSCI	Investment of equipment yearly	PACSI
Existing	Three Buses SE, DENO, DENC	1,397,500.00	X	X
Case A	Upgrade SE Bus to DENO	1,160,000.00	50,000	187,500
Case B	Upgrade SE Bus to DENC	1,001,666.00	75,000	320,834
Case C	Upgrade DENO Bus to DENC	1,376,259.00	25,000	-3,759
Case D	Upgrade SE Bus to DENO & Upgrade DENO Bus to DENC	1,138,750.00	75,000	183,750
Case E	Upgrade SE Bus to DENC & Upgrade DENO Bus to DENC	980,417.00	100,000	317,083

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Conclusions

New industrial plant reliability indices based on the plant critical equipment have been proposed in this thesis. The proposed industrial plants reliability indices compared with the existing industrial plants reliability indices. The effect of re-arranging the loads in the industrial plant substation is evaluated through case studies. In order to select the best upgrading option, five case studies were carried out in this thesis.

When comparing the existing reliability indices to the proposed indices, it was found that the existing indices don't consider the plant re-startup time, consider non-critical loads and vary with by changing the KVA rating which gives inaccurate figures of the plant reliability evaluation. Different industrial plants substation configurations can be evaluated using the proposed reliability indices. The best upgrading option for the existing substations selected based on the plant annual cost saving index.

7.2 Recommendations for future work

Future work can be continued to evaluate the existing commercial and residential reliability indices. The cost saving and upgrading options for the residential and commercial can also be studied.

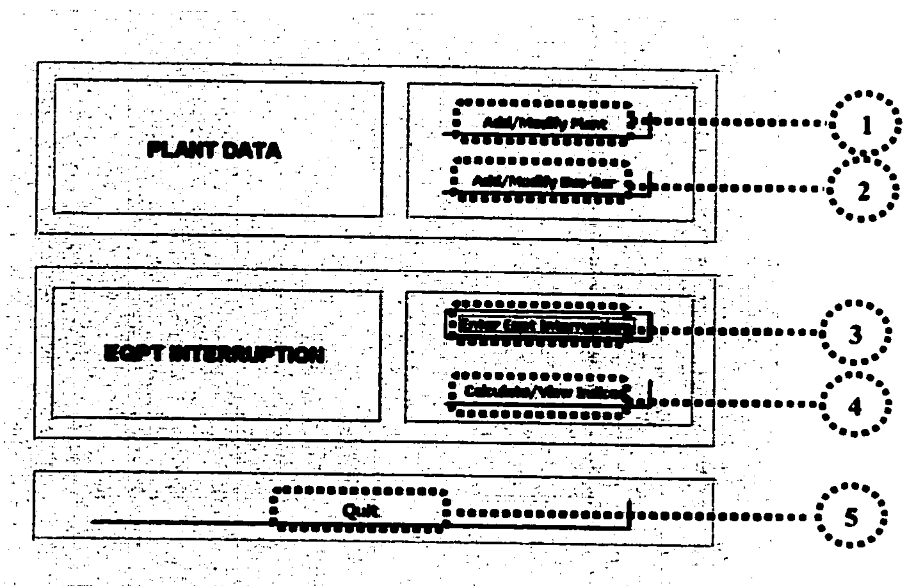
Appendices

Appendix A: Industrial Plant Soft ware User Guide

The industrial plant software is a Microsoft Access Program developed in order to calculate the proposed industrial plant reliability indices. The user needs to enter the industrial plant input data in the program which will calculate and report the industrial plant reliability indices for that plant. The program is described in details in the following user guide tables.

Main Form

The Main Form is displayed when the Database is started.



1 Add/Modify Plant: Opens the Form for entering Plant details

2 Add/Modify Busbar: Opens the Form for entering Busbar

details

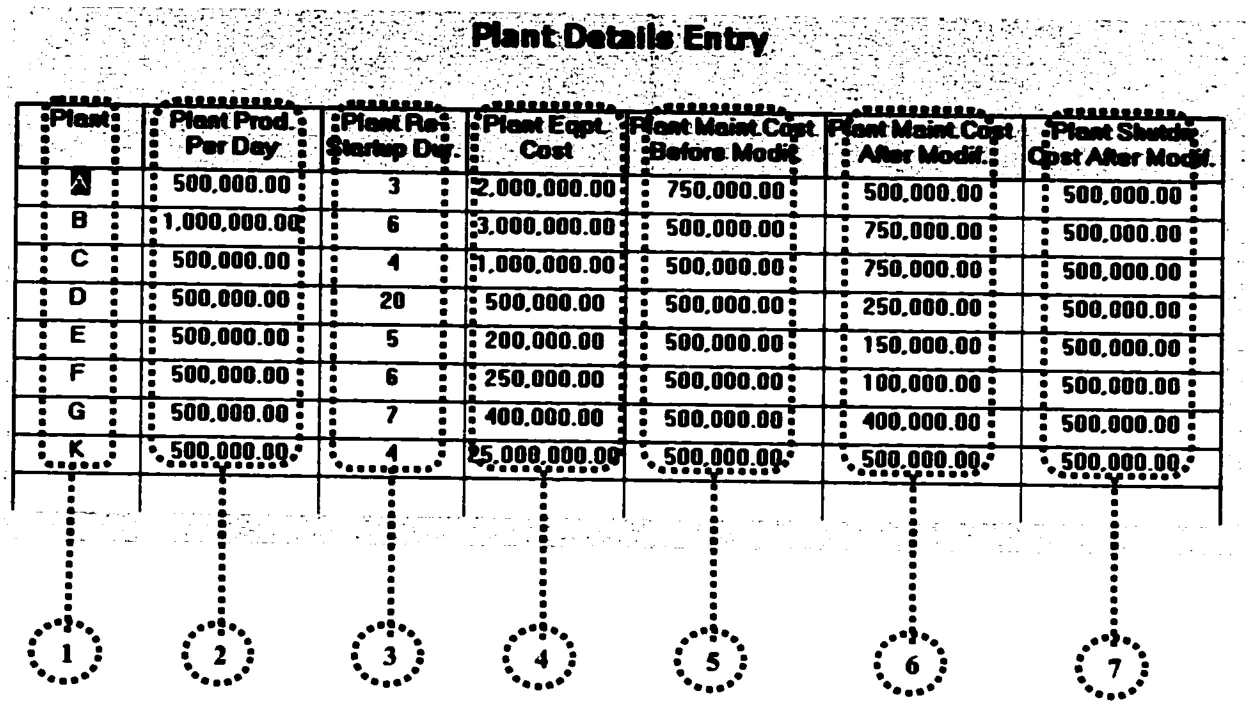
3 Enter Eqpt. Interruption: Opens the Form for entering equipment interruptions

4 Calculate/View Indices: Opens the form for calculating and viewing Indices

5 Quit: Close the Database

Add/Modify Plant Form

This form allows entry / modification of data related to the Plant.


Plant Details Entry

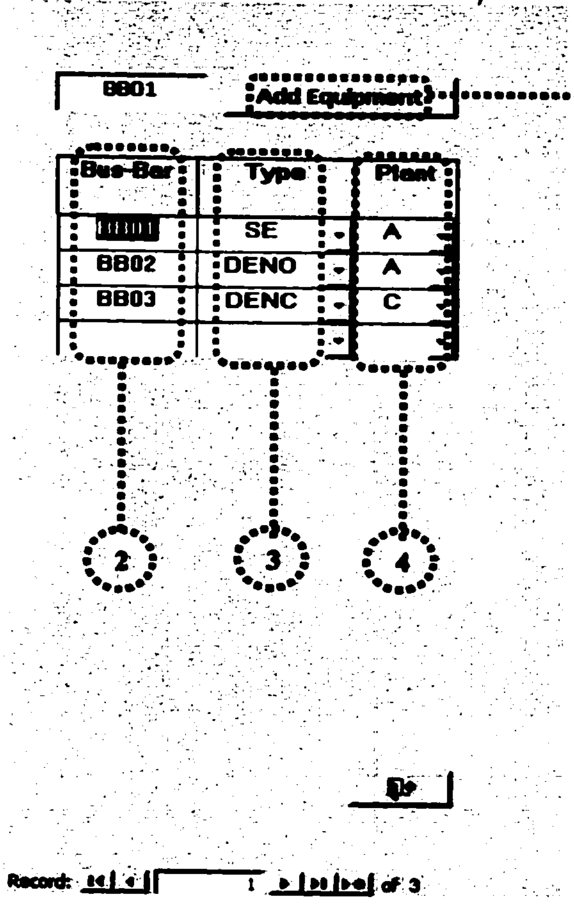
Plant	Plant Prod. Per Day	Plant Re-Startup Dur.	Plant Eqpt. Cost	Plant Maint.Cost Before Modif.	Plant Maint.Cost After Modif.	Plant Shutdn. Cost After Modif.
A	500,000.00	3	2,000,000.00	750,000.00	500,000.00	500,000.00
B	1,000,000.00	6	3,000,000.00	500,000.00	750,000.00	500,000.00
C	500,000.00	4	1,000,000.00	500,000.00	750,000.00	500,000.00
D	500,000.00	20	500,000.00	500,000.00	250,000.00	500,000.00
E	500,000.00	5	200,000.00	500,000.00	150,000.00	500,000.00
F	500,000.00	6	250,000.00	500,000.00	100,000.00	500,000.00
G	500,000.00	7	400,000.00	500,000.00	400,000.00	500,000.00
K	500,000.00	4	25,000,000.00	500,000.00	500,000.00	500,000.00

1	**Plant:**	Enter a unique Plant Name
2	**Plant Production Per Hour:**	Enter amount
3	**Plant Re-startup Duration:**	Enter duration in hours
4	**Plant Eqpt. Cost**	Cost of Equipment for

		Modification
5	**PMCB**	Plant Maint. Cost Before Modification
6	**PMCA**	Plant Maint. Cost After Modification
7	**PSCA**	Plant Shutdown Cost After Modification

Add/Modify Busbar Form

This form is used to enter / modify data for Busbars

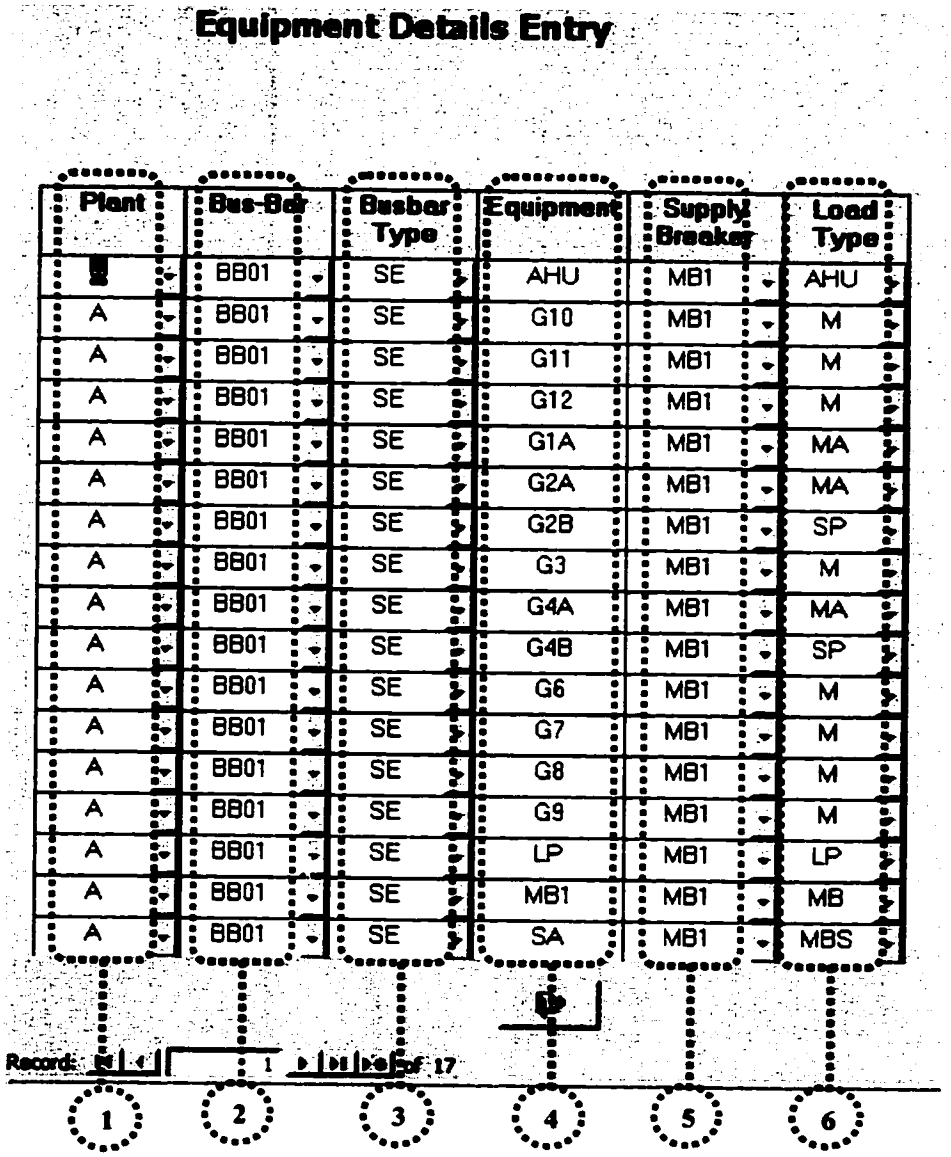


1	**Add Eqpt.**	Open Equipment Entry Form
2	**Busbar:**	Enter Busbar No.
3	**Busbar Type:**	Select the Type of Busbar: SE : Single Ended

	DENO:	Double Ended, with Normally Open Tie Breaker
	DENC:	Double Ended, with Normally Closed Tie Breaker
4 **Plant:**		Select the Plant to which this Busbar belongs.

Add/Modify Equipment Form

This form is used to enter / modify data for individual Equipment



Equipment Details Entry

Plant	Bus-Bar	Busbar Type	Equipment	Supply Breaker	Load Type
[illegible]	BB01	SE	AHU	MB1	AHU
A	BB01	SE	G10	MB1	M
A	BB01	SE	G11	MB1	M
A	BB01	SE	G12	MB1	M
A	BB01	SE	G1A	MB1	MA
A	BB01	SE	G2A	MB1	MA
A	BB01	SE	G2B	MB1	SP
A	BB01	SE	G3	MB1	M
A	BB01	SE	G4A	MB1	MA
A	BB01	SE	G4B	MB1	SP
A	BB01	SE	G6	MB1	M
A	BB01	SE	G7	MB1	M
A	BB01	SE	G8	MB1	M
A	BB01	SE	G9	MB1	M
A	BB01	SE	LP	MB1	LP
A	BB01	SE	MB1	MB1	MB
A	BB01	SE	SA	MB1	MBS

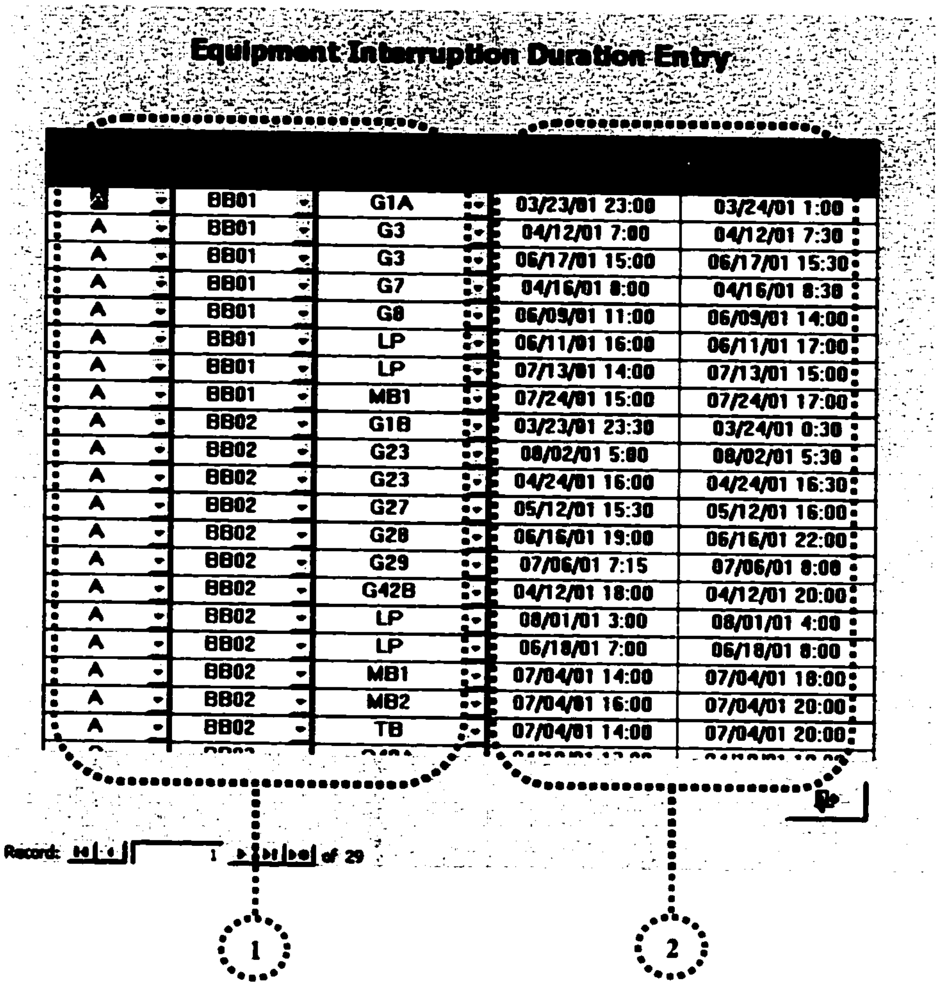
Record: 1 of 17

1 2 3 4 5 6

1	**Plant:**	Select the Plant in which this equipment exists.
2	**Busbar:**	Enter the busbar supplying the equipment
3	**Busbar Type:**	Type of busbar
4	**Equipment:**	Name/No. of the equipment
5	**Breaker No:**	Select the breaker to which this equipment is connected
6	**Load Type**	The Plant Interruption depends on the type of load.

MA:	Main Eqpt. If an equipment has a spare. Does not interrupt the plant unless the spare equipment is also tripped.
SP:	Spare Eqpt. This equipment is the spare of the main equipment. Causes plant interruption when tripped along with main equipment
M:	Main Equipment without spare. Causes plant interruption when tripped
MB:	Main breaker. Causes plant interruption when tripped. All the equipment connected to the breaker are tripped.
MBS	Supply Breaker to another Bus bar
AHU:	Air Handling Unit. Does not cause plant interruption
LP:	Lighting Panel. Does not cause plant interruption.

Equipment Interruption Entry Form



A	BB01	G1A	03/23/01 23:00	03/24/01 1:00
A	BB01	G3	04/12/01 7:00	04/12/01 7:30
A	BB01	G3	06/17/01 15:00	06/17/01 15:30
A	BB01	G7	04/16/01 8:00	04/16/01 8:30
A	BB01	G8	06/09/01 11:00	06/09/01 14:00
A	BB01	LP	06/11/01 16:00	06/11/01 17:00
A	BB01	LP	07/13/01 14:00	07/13/01 15:00
A	BB01	MB1	07/24/01 15:00	07/24/01 17:00
A	BB02	G18	03/23/01 23:30	03/24/01 0:30
A	BB02	G23	08/02/01 5:00	08/02/01 5:30
A	BB02	G23	04/24/01 16:00	04/24/01 16:30
A	BB02	G27	05/12/01 15:30	05/12/01 16:00
A	BB02	G28	06/16/01 19:00	06/16/01 22:00
A	BB02	G29	07/06/01 7:15	07/06/01 8:00
A	BB02	G42B	04/12/01 18:00	04/12/01 20:00
A	BB02	LP	08/01/01 3:00	08/01/01 4:00
A	BB02	LP	06/18/01 7:00	06/18/01 8:00
A	BB02	MB1	07/04/01 14:00	07/04/01 18:00
A	BB02	MB2	07/04/01 16:00	07/04/01 20:00
A	BB02	TB	07/04/01 14:00	07/04/01 20:00

Record: 1 of 29

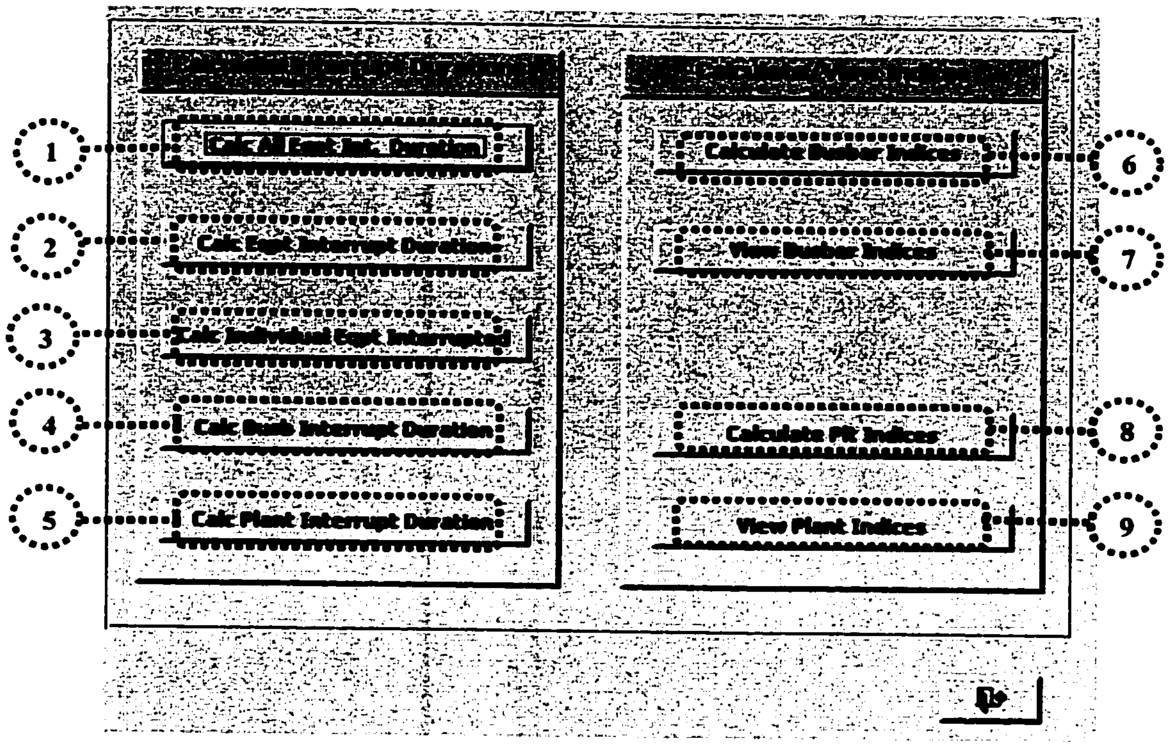
1

2

1	**Equipment**	Details of Interrupted Equipment
2	**Interruption Start and End**	Start and End Date of Interruption

Calculate/View Indices Form

This form is used to calculate and view plant indices.



1 Calculate All Equipment Interruption Duration:
Enumerates all equipment in the plant/busbar, then calculates the total number and duration of equipment interruption

2 Calculate Equipment Interruption Duration
Calculates the duration of interruption of all equipment which causes an interruption of the busbar / plant.

3 Calculate Individual Eqpt. Interrupted
Calculates Distinct Equipment Interrupted within the busbar

4 Calculate Busbar Interruption Duration
Calculates the interruption duration of Busbar due to interrupted equipment. If the duration of two equipment overlap, the two interruptions are combined.

5 Calculate Plant Interruption Duration
Calculates the Interruption of Plant due to busbar interuption. If the

duration of two busbars overlap, the two interruptions are combined.

6 Calculate Busbar Indices
Calculate Indices for each busbar, using the Busbar interruption durations

7 View Busbar Indices
Opens the Busbar Indices Report

8 Calculate Plant Indices
Calculate Plant Indices, using Plant Interruption durations

9 View Plant Indices
Opens the Plant Indices Report

Busbar Indices Report

Industrial Plants Reliability Indices

Plant	A	BusBar	BB01

Plant Production per Hour	500,000.00	Plant Re-Startup Duration	3

Equipment Table

No.	Busbar	Equipment	Load Type	Supply Breaker	No of Interruptions	Total Dur of Interruptions
1	BB01	G7A	MA	MB1	1	1.5
2	BB01	G2	M	MB1	0	0
3	BB01	G7B	SP	MB1	1	2
4	BB01	G4	M	MB1	0	0
5	BB01	G3	M	MB1	0	0
6	BB01	LP1	LP	MB1	1	2
7	BB01	AHU1	AHU	MB1	0	0
8	BB01	G8A	MA	MB1	1	3.05
9	BB01	G1	M	MB1	1	1
10	BB01	G9	M	MB1	0	0
11	BB01	G8	M	MB1	0	0
12	BB01	LP2	LP	MB1	0	0
13	BB01	AHU2	AHU	MB1	1	18
14	BB01	MB1	MB	MB1	1	28.5

1

Busbar Interruption Table

Plant	A	Busb	BB01	BBTyp	SE	TotEqpt	8

No	Eqpt Interrupted	BIntNo	EqptInt	BIntDur	BISD	BIFD
1	G8A	1	1	1	01/01/01. 2:02	01/01/01. 3:02
2	G1	1	1	1	05/14/01. 12:00	05/14/01. 13:00
3	MB1	1	8	28.5	08/16/01. 19:00	08/17/01. 23:30
	TOTALS	3	10	30.5		

2

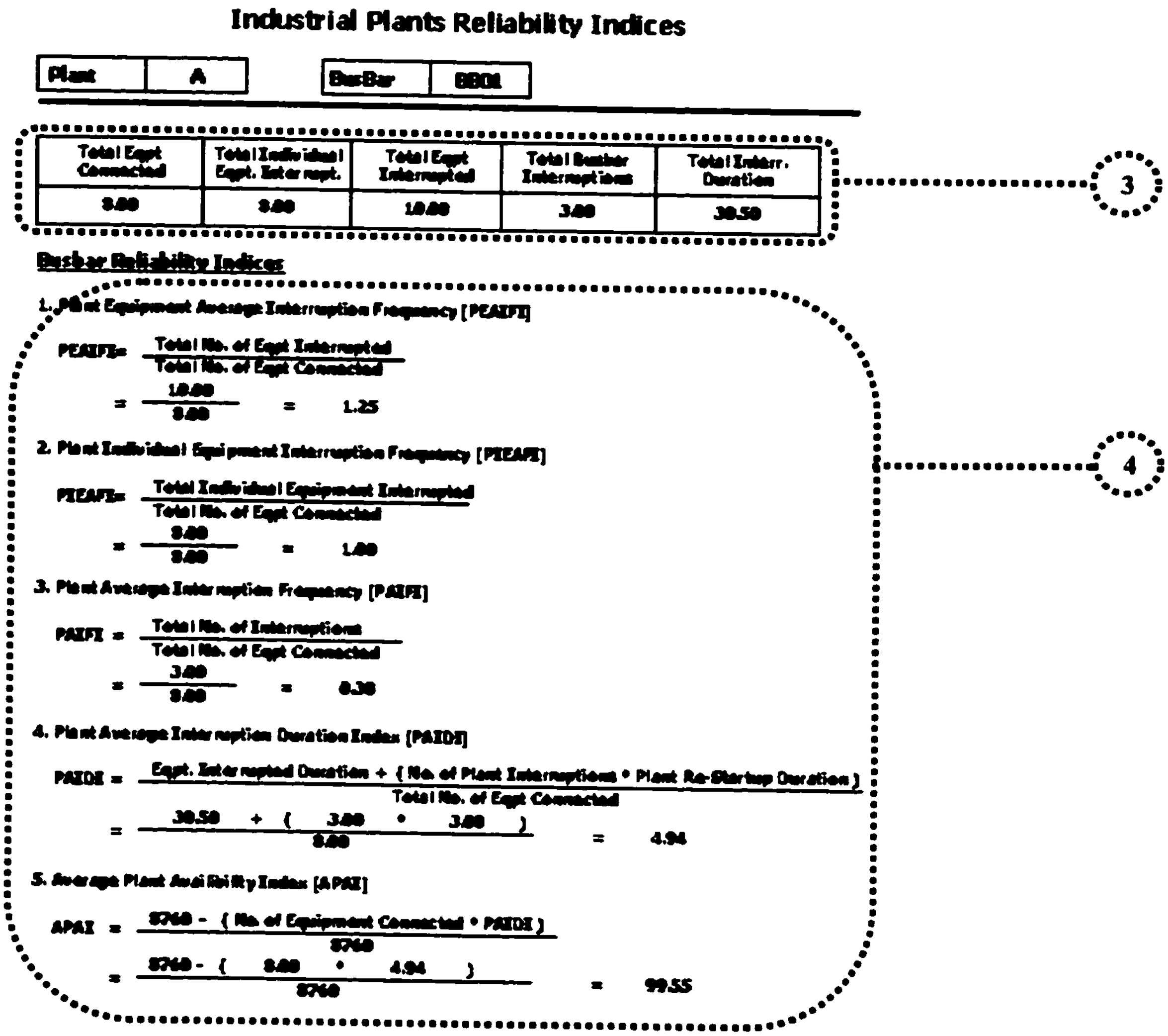
This report details the following:

1 Equipment Table

All equipment supplied by the busbar, and their individual interruptions and interruption durations.

2 Busbar Interruption Table

The type of busbar, the total no. of equipment connected to the busbar, and the interruption of the equipment, the duration of interruption, and the start time and end time of the interruption.



3 A summary table showing total equipment connected, total equipment interrupted, the total no. of interruptions and the total duration of interruption.

4 **Busbar Indices Calculation**
Calculation of the Indices

Industrial Plants Reliability Indices

Plant	A		BusBar	BB01

6. Plant Shut down Cost [PSC]

PSC = Plant Prod Cost per hour * (Eqpt. Int. Dur. + (No. of Int. in a Year * Plt. Startup Dur))

= 500,000.00 * (30.50 + (3.00 * 3.00)) = 822,916.67

Busbar Reliability Indices

PEAIFI	PIEAFI	PAIFI	PAIDI	APAI	PSC
1.25	1.00	0.38	4.94	99.55	822,916.67

5

5 Busbar Reliability Indices
A summary table showing the Busbar Indices

View Plant Indices Report

Industrial Plants Reliability Indices

Plant	A

Plant Production per Hour	500,000.00	Plant Re-Startup Duration	3

Busbar Interruption Table

Plant	A	Busb	BB01	BBTyp	SE	TotEqpt	8

No	Eqpt Interrupted	BIntNo	EqptInt	BIntDur	BIBD	BIFD
1	G8A	1	1	1	01/01/01. 2:02	01/01/01. 3:02
2	G1	1	1	1	05/14/01. 12:00	05/14/01. 13:00
3	MB1	1	8	28.5	08/16/01. 19:00	08/17/01. 23:30
TOTALS		3	10	30.5		

Plant	A	Busb	BB02	BBTyp	DENO	TotEqpt	9

No	Eqpt Interrupted	BIntNo	EqptInt	BIntDur	BIBD	BIFD
1	TIE_MB1	1	4	1.02	01/01/01. 1:01	01/01/01. 2:02
2	MB1_MB2	1	9	10.17	08/18/01. 10:50	08/18/01. 21:00
3	G13	1	1	2	08/18/01. 11:00	08/18/01. 13:00
TOTALS		3	14	13.19		

Plant	A	Busb	BB03	BBTyp	DENC	TotEqpt	9

No	Eqpt Interrupted	BIntNo	EqptInt	BIntDur	BIBD	BIFD
1	G40	1	1	0.67	01/01/01. 12:20	01/01/01. 13:00
2	G3a	1	1	0.17	08/18/01. 20:50	08/18/01. 21:00
3	MB1_MB2	1	9	1.5	09/09/01. 12:30	09/09/01. 14:00
TOTALS		3	11	2.34		

1

Plant Interruption Table

Plant	A

No	Busbars Interrupted	PIntNo	PIntDur	PIBD	PIFD
1	BB02. BB01	1	2.02	1/1/2001 1:01:00 AM	1/1/2001 3:02:00 AM
2	BB03	1	0.67	1/1/2001 12:20:00 PM	1/1/2001 1:00:00 PM
3	BB01	1	1	5/14/2001 12:00:00 PM	5/14/2001 1:00:00 PM
4	BB02. BB01	1	38.87	8/16/2001 10:30:00 AM	8/17/2001 11:30:00 PM
5	BB02	1	2	8/18/2001 11:00:00 AM	8/18/2001 1:00:00 PM
6	BB03	1	0.17	8/18/2001 8:50:00 PM	8/18/2001 9:00:00 PM
7	BB03	1	1.5	9/9/2001 12:30:00 PM	9/9/2001 2:00:00 PM
TOTALS		7	44.03		

2

This report details the following:

1 Busbar Interruption Table
The type of busbar, the total no. of equipment connected to the busbar, and the interruption of the equipment, the duration of interruption, and the start time and end time of the interruption.

2 Plant Interruption Table
A consolidation of the busbar interruption tables, wherein common durations are combined into one.

Industrial Plants Reliability Indices

Plant	A

Total Eqpt Connected	Total Individual Eqpt. Interrupt.	Total Eqpt Interrupted	Total Interruptions	Total Interr. Duration
26.00	26.00	35.00	7.00	44.03

3

Plants Reliability Indices

1. Plant Equipment Average Interruption Frequency [PEAIFI]

$$\text{PEAIFI} = \frac{\text{Total No. of Eqpt Interrupted}}{\text{Total No. of Eqpt Connected}}$$

$$= \frac{35.00}{26.00} = 1.35$$

2. Plant Individual Equipment Interruption Frequency [PIEAFI]

$$\text{PIEAFI} = \frac{\text{Total Individual Equipment Interrupted}}{\text{Total No. of Eqpt Connected}}$$

$$= \frac{26.00}{26.00} = 1.00$$

3. Plant Average Interruption Frequency [PAIFI]

$$\text{PAIFI} = \frac{\text{Total No. of Interruptions}}{\text{Total No. of Eqpt Connected}}$$

$$= \frac{7.00}{26.00} = 0.27$$

4

4. Plant Average Interruption Duration Index [PAIDI]

$$\text{PAIDI} = \frac{\text{Eqpt. Interrupted Duration} + (\text{No. of Plant Interruptions} * \text{Plant Re-Startup Duration})}{\text{Total No. of Eqpt Connected}}$$

$$= \frac{44.03 + (7.00 * 3.00)}{26.00} = 2.50$$

5. Average Plant Availability Index [APAI]

$$\text{APAI} = \frac{8760 - (\text{No. of Equipment Connected} * \text{PAIDI})}{8760}$$

$$= \frac{8760 - (26.00 * 2.50)}{8760} = 99.26$$

3 A summary table showing total equipment connected, total equipment interrupted, the total no. of interruptions and the total duration of interruption.

4 Plant Indices Calculation
Calculation of the Indices

Industrial Plants Reliability Indices

Plant	A

6. Plant Shutdown Cost [PSC]

PSC = Plant Prod Cost per hour * (Eqpt. Int. Dur. + (No. of Int. in a Year * Pl. Startup Dur))

= 500,000.00 * (44.83 + (7.00 * 3.00)) = 1,354,791.67

7. Cost Savings in 5 Years

CS5Y = ((PSC - PSC Aft. Modif) + (Pl Maint Cost Bef. Modif - Pl Maint Cost Aft. Modif)) * 5 - Plant Equipment Cost

= ((1,354,791.67 - 500,000.00) + (750,000.00 - 500,000.00)) * 5 - 2,000,000.00

= 3,523,958.33

Plant Reliability Indices

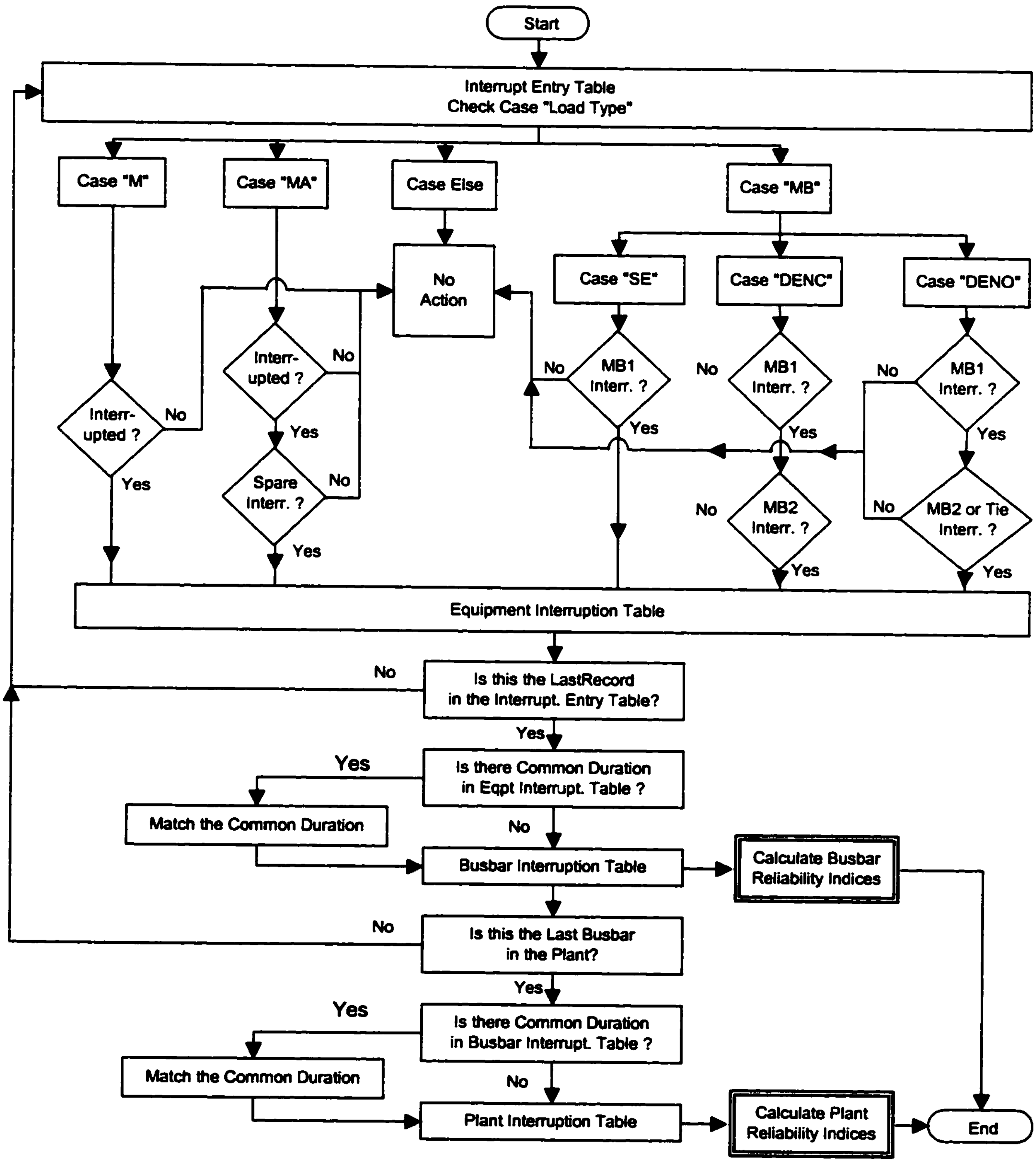
PEAIFI	PIEAFI	PAIFI	PAIDI	APAI	PSC	CS5Y
1.35	1.00	0.27	2.50	99.26	1,354,791.67	3,523,958.33

5

5 Plant reliability Indices
A summary table showing the Plant Indices

Appendix B

INDUSTRIAL PLANTS RELIABILITY INDICES CALCULATION FLOWCHART



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